NASA-CR-197489

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VERY HIGH ENERGY GAMMA RAY EXTENSION OF GRO OBSERVATIONS

NASA GRANT NAG5-1381

Final Report

For the period 01 June 1990 through 31 May 1994

Principal Investigator
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December 1994

Prepared for
National Aeronautics and Space Administration
Greenbelt, Maryland 20771

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The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

(NASA-CR-197489) VERY HIGH GAMMA RAY EXTENSION OF GRO OBSERVATIONS Final Report, 1 Jun. 1990 - 31 May 1994 (Smithsonian Astrophysical Observatory) 35 p

N95-17421

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G3/93 0033905

I. Progress Report

Membership of Collaboration (as of October 1994)

Smithsonian Astrophysical Observatory

T. C. Weekes (Astrophysicist)
J. Buckley (Post-doctoral Associate)
M. Chantell (Grad. student (UA))
V. Connaughton (Grad. student (UCD))
K. Harris (Engineer)
T. Lappin (Observer)

Iowa State University

R. C. Lamb (Professor)
D. A. Lewis (Professor)
D. Bird (Post-doctoral associate)
F. Krennrich (NASA Post-doctoral associate)
G. Mohanty (Grad. student)
J. Zweerink (Grad. student)
F. Samuelson (Grad. student)
C. Fenlason (Grad. student)
R. Hoversten (Grad. student)

University of Michigan

C. W. Akerlof (Professor)
D. I. Meyer (Professor)
M. Schubnell (Post-doctoral associate)

Purdue University

J. Gaidos (Professor)
C. Wilson (Post-doctoral associate)
G. Sembroski (Post-doctoral associate)

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D. J. Fegan (Senior Lecturer)
N. A. Porter (Professor Emeritus)
S. Fennell (Grad. student)
J. Hagen (Grad. student)
R. Lessard (Grad. student)
J. Quinn (Grad. student)
J. McEnery (Grad. student)

St. Patrick's College, Maynooth, Ireland

M. F. Cawley (Lecturer)

University of Leeds, United Kingdom

A. M. Hillas (Professor)
J. Rose (Lecturer)
S. Biller (Post-doctoral Associate)
M. West (Grad. student)

Collaboration Responsibilities

The division of responsibilities between different institutions in the Whipple Gamma Ray Collaboration are listed below; however these are only guidelines and the divisions are not hard and fast.

The observing program is agreed upon by the collaboration in bi-annual meetings in which all groups are represented. The observing mode and data reduction method to be used is also agreed upon at that time.

The on-going observing program is the prime responsibility of the local Smithsonian group (aided by the resident ISU postdoc, David Bird). This involves the detailed scheduling of observing (sources and observers). Fast-look analysis is performed locally and the data is prepared for distribution to the five other centers. The local group is responsible for routine maintenance of the telescopes and cameras. Observing is shared by all groups with visiting observers sharing shifts with local staff.

Responsibility for data reduction on specific sources is assumed by individuals within the collaboration. Usually students are assigned specific sources for dissertation studies. Data on each source is independently reduced by at least two observers. New data reduction methods are developed and distributed for routine analysis. Some centers take responsibility for specific tasks e.g. spectrum analysis (ISU, Leeds), periodicity analysis (Michigan, Leeds), etc.

Technical aspects of the experiment are the responsibility of the individual groups e.g. 11m electronics (Michigan), 10m electronics (SAO), phototubes (ISU), cabling (Purdue), tracking control, ccd cameras (UCD), data acquisition software (Leeds), CAMAC interface (Purdue), data acquisition upgrades (ISU), 10m optics (SAO), 11m optics (ISU, Michigan), etc.

Simulations were originally the responsibility of ISU and Leeds; they are now carried out at all centers. Long-term planning has been the responsibility of Purdue. All groups are involved in the design studies for the Phase I development.

Progress Reports: Science

The May 1994 Markarian Flare at Whipple and EGRET Energies

Since its discovery by us at TeV energies (Punch et al. 1992), we have continued a program of monitoring the emission from Markarian 421, coordinated with observations taken by the EGRET detector. (These coordinated observations are partially supported by NASA Gamma Ray Observatory guest investigator grants.) In May 1994, an outburst was detected in which the intensity of the source increased by nearly an order-of-magnitude over its pre-outburst, "quiescent" level. A paper describing these results has now been accepted for publication in the Astrophysical Journal Letters, and a copy in included in the appendix.

In figure 1, the on- and off-source alpha distributions for the maximum observed emission of Markarian 421 during this outburst are shown. A strong excess near zero degrees, indicative of gamma-ray emission from the direction of Markarian 421, is apparent in both datasets. A paper describing the combined Whipple and EGRET observations during April and May 1994, as well observations at lower photon energies is in preparation (Macomb et al. 1995). In figure 2 the variation of the net gamma-ray flux from Markarian 421 observed by the Whipple gamma-ray telescope is shown from 1 April through 12 June. In addition to the strong May 15 outburst a second ($\sim 3\sigma$) outburst in June is evident. In figure 3, the corresponding EGRET observations are shown. There is no evidence within the EGRET 1 week observation in May for a flare on the time scale ($\sim$ 2 days) as observed at TeV energies. Future multi-wavelength monitoring of Markarian 421 is planned for the spring of 1995.

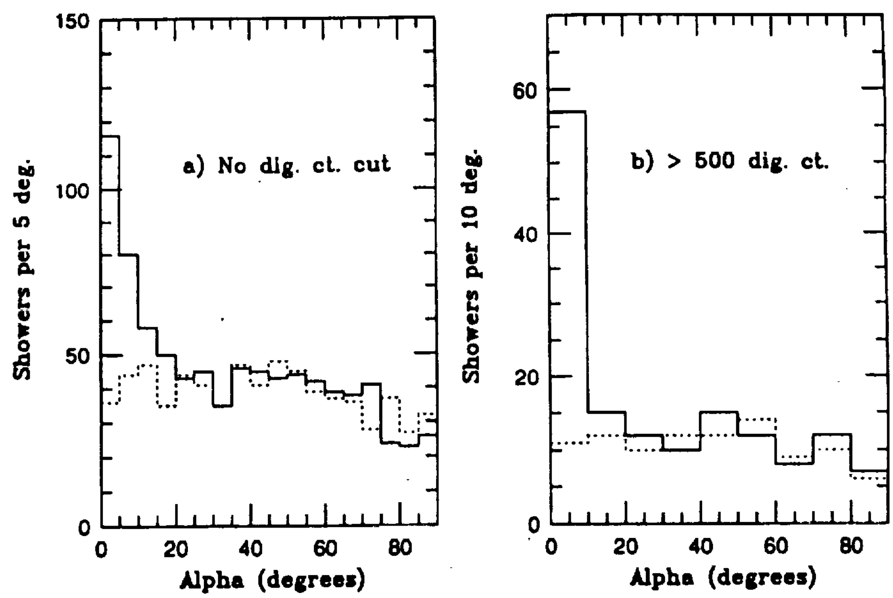

Figure 1. On- and off-source alpha distributions for Markarian 421 for 15.25 May 1994 (UT). The distributions are for those showers for which the other supercuts selection criteria have been satisfied. The duration of each observation is 28.3 minutes. a) No selection has been made on the number of digital counts contained in a shower image. b) Only those showers which have more than 500 digital counts are retained. This latter selection is approximately equivalent to raising the threshold energy from 250 to 500 GeV.

AGN's

Since October, 1991 the observation of AGN's has been given high priority in the Whipple Observatory Collaboration gamma-ray observing program, following the successful detection by EGRET of 3C279 (Hartman et al. 1992). In all 35 objects were studied (14 of which had been detected at GeV energies by EGRET).

No statistically significant excesses were seen and upper limits were calculated at the 3σ level. In view of the reported variability of these objects it is important to emphasize that these limits pertain only for the limited epoch of the observations. A preliminary

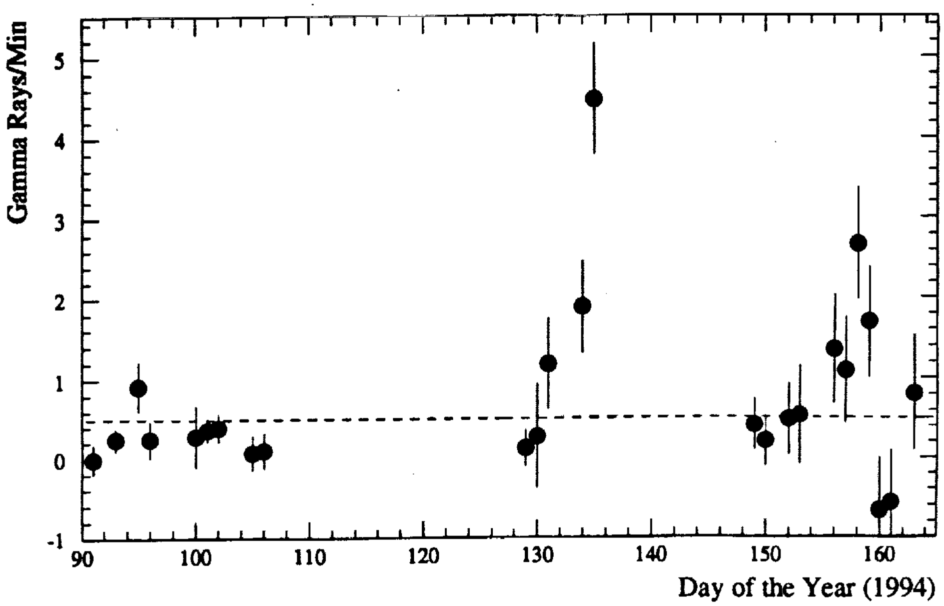

Figure 2. The variation in net gamma-rays/minute for the Markarian 421 observations from 1 April, 1994 (day 91) through 12 June, 1994 (day 163). The peak intensity of 15.25 May (day 135) occurs 27 hours prior to a reported X-ray high state (Takahashi et al 1994). Data from 16-28 May (days 136-148) were not obtained due to bright moon conditions. The dashed line shows the 1994 quiescent level (Schubnell et al. 1995).

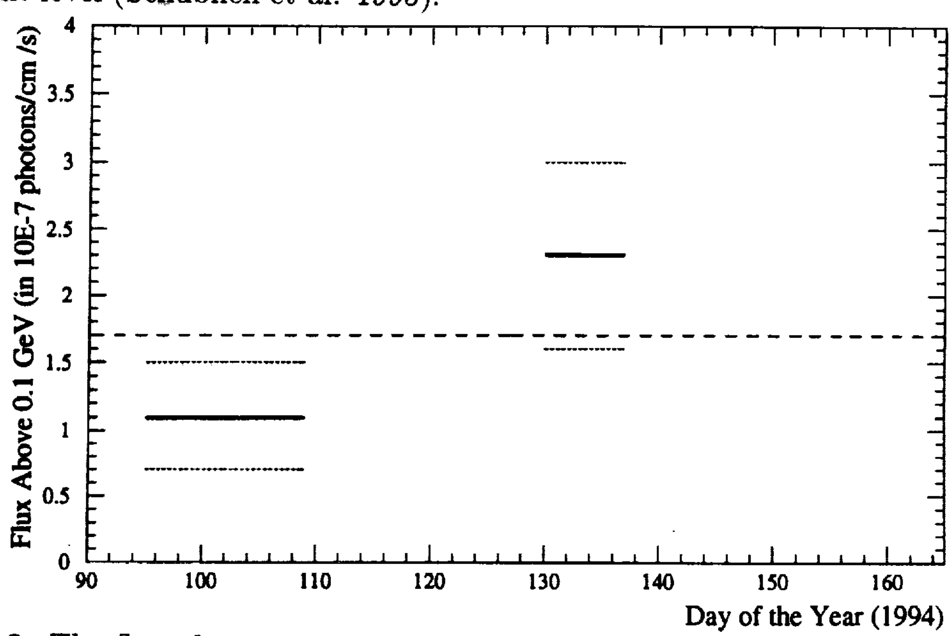

Figure 3. The flux above 100 MeV as observed by the EGRET detector during April and May 1994. While it seems that the flux during May is a factor of two higher than during April, neither flux is significantly different than the average flux from all EGRET observations (the dashed line at 1.7×10^{-7}photons/cm^2/s).

paper describing these results is has been presented (Kerrick et al. 1993). The high energy gamma-ray spectrum of several of the EGRET-detected sources for which energy spectra have been published are plotted in figure 4 together with upper limits from the air shower experiments and the upper limits reported here.

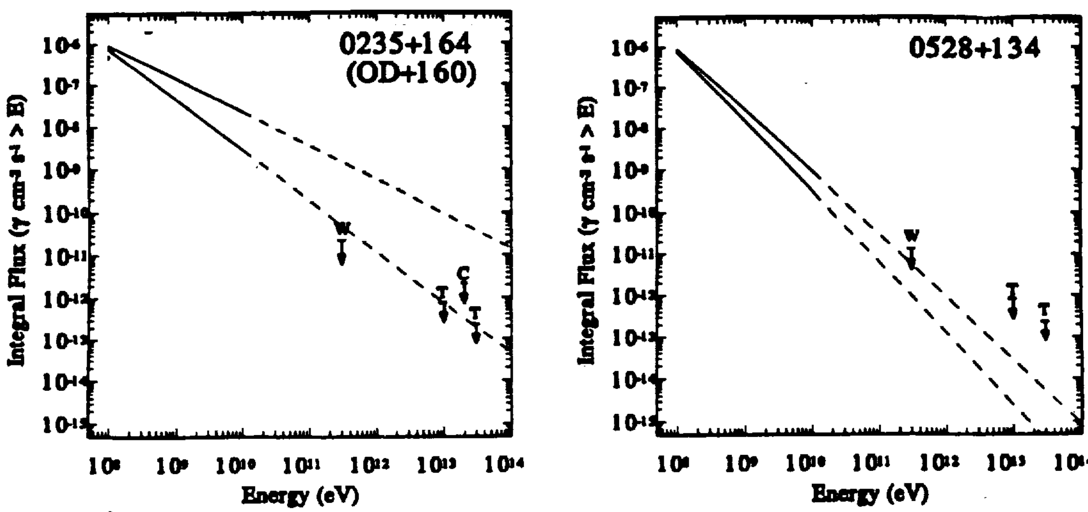

Figure 4. Selected AGN spectra.

The observations reported here were undertaken to test the hypothesis that some or all of the EGRET-detected AGN's had detectable components in the TeV energy region. With the exception of Markarian 421 none of the 14 AGN's detected by EGRET which were included in this observing program were detected. Since the observation of Markarian 421 shows that for flat spectrum sources the Whipple telescope is more sensitive than EGRET the search was extended to objects with somewhat similar properties to Markarian 421 but which were not detected by EGRET; again no emission was detected. The conclusions from these null results are restricted by the fact that almost all the AGN's detected by EGRET are time-variable (as is Markarian 421 at TeV energies (Kerrick et al. 1994)). However a reasonable conclusion is that the observable spectrum of AGN's shows a steepening between 10 GeV and 300 GeV. Such a steepening could have three origins: (i) an inherent steepening in the particle acceleration spectrum in the AGN or in the gamma-ray production spectrum, (ii) absorption of the gamma rays close to the AGN, or (iii) absorption of gamma-rays in intergalactic space.

Bursts

An extensive search has been made in the Whipple Data-base for bursts on time-scales of one second. A preliminary rêport on this work was presented at the ICRC in Calgary (Connaughton et al. 1993a) and at the Huntsville Meeting on Gamma Ray Bursts (Connaughton et al. 1993b). The database used was that of all five years of observations made with the Whipple High Resolution Camera from 1988 through 1993. The method used was as follows: all candidate gamma-rays were selected based on their Length and Width. This rejected more than 98% of the background events. Any cluster of three or four events occurring in one second was then selected as a potential burst. Each such cluster was then examined to see if the orientation of the axes of the events was consistent with all 3 (or 4) events originating from the one point in the sky. A control group was formed by randomizing the times of arrival and image parameters in each run. The observed excesses were not significant and an upper limit of 2.7×10^4 bursts/year-steradian corresponding to a limit on the fluence of 3.3×10^{-8} erg/sec was derived. A paper describing this result is in preparation (Connaughton et al. 1995).

Since May 1994 the Whipple Observatory has been linked to the BACODINE network in which notification of the position of a gamma- ray burst detected by BATSE on the Compton GRO is received within minutes of its detection. The Whipple telescope is then slewed to the source position and a search is made within the burst error box for the next three hours. The expected useful rate of BATSE notifications is 0.5/month. To date (because of the summer close- down and equipment upgrading) only one useful notification has been received; no excess was noted but the burst was weak and the position was at very low elevation. The search continues.

Supernova Remnants

Over the last year a number of supernovae remnants (both shell-type and plerions) have been observed. At the beginning of the 1993-94 we drew up a source list, selecting objects on the basis of their radio luminosity, distance, angular size, morphology (shell or plerion) and age as well as a possible association with unidentified EGRET sources. Our observations have concentrated on a number of observations of shell type SNR's.

Tycho's SNR is particularly well suited for observations with the imaging technique since it has a small angular size (~6 arcmin). Currently for Tycho we have a 3σ upper limit of $9\times10^{-12}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ which is a factor of two above the model of Drury, Aharonian, and Völk (1994).

For the remnant G78.2+2.1, Aharonian (1994) predicts a gamma-ray flux above 1 TeV of approximately $1.8\times10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for a spectrum of $E^{-2.1}$. This flux is comparable to that of the Crab Nebula, and although it is spread out over a 1° source it should be easily detectable. Analysis of this data is currently in progress.

Simulations and Energy Spectra

A 1 TeV gamma-ray initiated air shower produces a pancake of Cherenkov light that is about 200 meters in diameter and about one meter thick when it strikes the ground. At the edge of the pancake the light intensity falls exponentially and, at energies above 1 TeV, there is a central spike in intensity which grows rapidly with increasing gamma-ray energy as shown in figure 5.

In the portion of the pancake between the central spike and the edge, the light intensity is roughly proportional to the energy of the incident gamma. Light from this region is suitable for an estimate of the energy. Unfortunately, nature only provides gamma's at random locations relative to the telescope and the distance to the core of the shower can only be estimated. This limits the telescope energy resolution. There are also large fluctuations in how deeply the initial gamma penetrates the atmosphere before producing

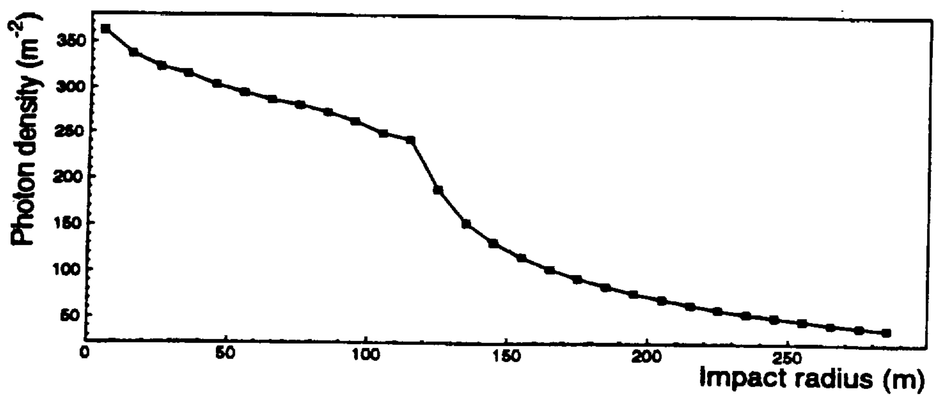

Figure 5. Lateral distribution of Cherenkov light intensity for a 1 TeV gamma-initiated air shower. The central spike grows rapidly with energy and exhibits large shower-to-shower fluctuations. Light intensity at the edge falls approximately exponentially.

the first e^+e^- pair and also in the depth at which the next few interactions occur. These fluctuations change the Cherenkov light intensity at ground level further limit the energy resolution of the telescope. Nevertheless, because of large collection area and the resulting relatively high event rate, it is possible to make accurate determinations of spectra.

In order to extract as much information about the energy spectra of TeV sources as possible, we have developed Monte Carlo codes for simulation of the electromagnetic cascade, Cherenkov light generation, atmospheric transmission and the response of the telescope. There are several results from these studies.

For instance, we have found that gamma-ray selection methods, (e.g. supercuts) designed to maximize signal by minimizing cosmic-ray background while keeping a large fraction of the gamma's generally are not optimal for determining source spectra. The reason for this is that since energy spectra fall as $E^{-\gamma}$ such methods will be biased to preferentially pick out gamma's near the telescope threshold. This effect can be seen by examining the variation with energy of the telescope collection area as shown in figure 6 for the supercuts selection.

We have modified the supercuts procedure to reject the maximum number of cosmic-ray background events while keeping the collection area for gamma's approximately constant. This results in the curve labeled extended supercuts (ESC) in Fig. 6. As can be seen from the figure, it is possible to determine spectra from about 0.3 to beyond 10 TeV using this procedure. The energy resolution of the telescope is $\Delta E/E \sim 0.4$ limited by the uncertainties in the core location and vertical development of the shower as described above.

We have extracted TeV spectra for the Crab and for Markarian 421 as published in Lewis et al. (1993) and Mohanty et al. (1993) respectively. As a check of this procedure our collaborators at the University of Leeds, A.H. Hillas and M. West, have developed a different algorithm based on a completely independent set of simulations which yields a different result for the Crab spectrum (~20% difference in the exponent of the power-law

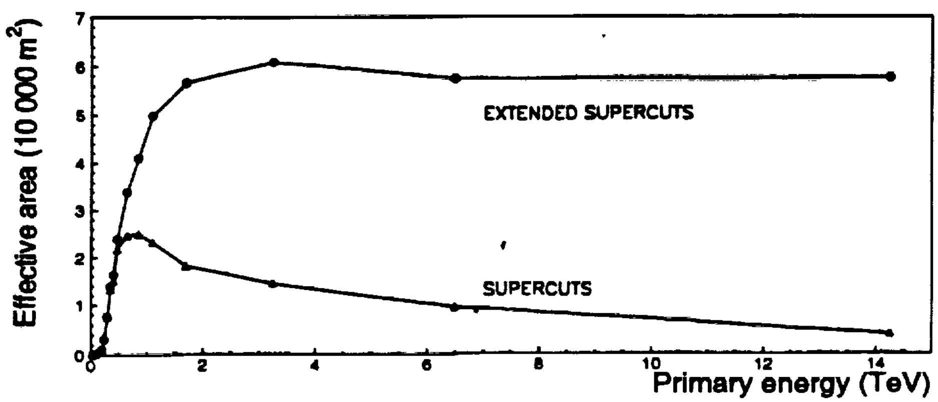

Figure 6. Collection area of the Whipple 10m telescope as a function of incident gamma-ray energy. The two curves correspond to supercuts (SC) and extended supercuts (ESC) as explained in the text.

spectrum). We have been working for some time to resolve these differences. A meeting to be held shortly at Iowa State University of the Leeds and ISU collaborators should settle the matter.

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Invited Talks, Publications, Proceedings.

INVITED TALKS

16th Texas Symposium on Relativistic Astrophysics and 3rd Symposium on Particles, Strings and Cosmology, Berkeley, California, Editors: C.Akerlof, M.Snednicki (1992), "Gamma-ray Astronomy above 100 GeV"

International Workshop "Towards a Major Atmospheric Cherenkov Detector - II"; Calgary, Canada, July, 1993. "One or Many?".

Rikken International Workshop on Electromagnetic Cascades, Tokyo, Japan, December, 1993. "TeV Gamma Ray Astronomy"

Three invited lectures on TeV Gamma Ray Astronomy at the NATO School on Gamma Ray Astronomy, Les Houches, France, January 25-February 4, 1994.

Workshop "Towards a Large Atmospheric Cherenkov Detector - III", Tokyo, Japan, May 25-27, 1994. "TeV Gamma Ray Astronomy". Introductory Lecture, (not given because of illness).

International Conference on the Physics and Astrophysics of Neutrinos, "Neutrino 94"; May 29-June 3, 1994; "TeV Gamma Ray Astronomy".

Workshop on "Particle Astrophysics for the Next Millennium", Snowmass, Colorado, July 1-10, 1994.

Workshop on "Towards a Next Generation Gamma Ray Detector", Stanford, California, September, 1994. "Outburst from Markarian 421"

Workshop on "Astrophysics of TeV Gamma Ray Sources", Heidelberg, Germany, October 3-7, 1994. Introductory Talk,

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APPENDIX

Detection of TeV photons from the active galaxy Markarian 421

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PHOTONS of TeV energy have been observed from a few sources in our Galaxy, notably the Crab Nebula[1]. We report here the detection of such photons from an extragalactic source, the giant elliptical galaxy Markarian 421. Mk 421 has a nucleus of the BL Lacertae type[2,3], and emission from it has been observed at radio[4–6], optical[3,6] and X-ray[6–8] frequencies, and most recently in the MeV–GeV bands, by the EGRET detector aboard the Compton observatory[9]. In March–June 1992, we observed Mk 421 with the Whipple Observatory γ-ray telescope[10], a ground-based detector that images Cerenkov light from air showers, and found a signal with statistical significance of 6σ above background. The flux above 0.5 TeV is 0.3 of that from the Crab Nebula. The source location agrees with the position of Mk 421 within the angular uncertainty (6 arc minutes) of the Whipple instrument. The fact that we have observed this relatively nearby source (redshift $z = 0.031$), whereas active galaxies and quasars that are brighter at EGRET energies but more distant have not been detected in the TeV energy range, may be consistent with suggestions[11,12] that TeV photons are strongly attenuated by interaction with extragalactic starlight.

The very-high-energy γ-ray telescope[10] at the Whipple Observatory images Cerenkov light from air showers on a two-dimensional array of 109 fast photomultipliers with a pixel size of 0.25°. Monte Carlo simulations[13,14] and repeated observations of the Crab Nebula[15,16] demonstrate that the Cerenkov light images of air showers induced by γ-rays can be reliably distinguished from those induced by cosmic-rays (that is, nucleons).

The most sensitive technique yet used by the Whipple group for this purpose ('supercuts'[17]) uses four parameters to characterize the roughly elliptical shower image. Two of these are the root-mean-square length and width of the ellipse. A third, 'distance', is the angular distance of the centroid of the shower image from the assumed source location in the image plane. A fourth parameter, 'alpha', gives the orientation of the image. Alpha is defined to be the angle between the major axis of the shower image and a line from its centroid to the assumed source location in the image plane. For γ-ray showers from a point-like source, alpha should be near 0° because the elliptical images point to the location of the source in the image plane. The supercuts procedure[17] selects showers with small size, at distances from 0.51° to 1.1°, and with values of alpha <15 degrees.

In Fig. 1*a*, the alpha distributions for on-source and off-source observations of Mk 421 are compared after the other supercuts selection criteria have been satisfied. For the region of alpha <15 degrees there is a 6.3σ excess, with 302 on-source showers and 166 off-source showers. These observations were made between 24 March and 2 June 1992 for a total of 7.5 hours on-source and an equal amount of time off-source. The excess corresponds to an average flux of 1.5×10^{-11} photons cm^{-2} s^{-1} above 0.5 TeV, equivalent to 0.3 times that of the Crab Nebula. If one assumes isotropic emission at a distance of 124 Mpc, then the corresponding luminosity is $\sim 10^{43}$ erg s^{-1}. But as Mk 421 is known to show jet-like behaviour, the actual TeV luminosity may be considerably less.

For comparison, the alpha distributions for the previously reported observations of the Crab Nebula[17] are shown in Fig. 1*b*. For the Crab Nebula the excess has a statistical significance of 34σ. For both sources, the data of Fig. 1 have been restricted to observations at elevations greater than 55°. The similarity between the Mk 421 excess in the small-angle region of Fig. 1 and the corresponding excess for the Crab Nebula corroborates the Mk 421 signal. As a measure of the stability of the Whipple detector, the on-source and off-source datasets contained 77,181 and 76,761 raw, uncut showers, respectively, a difference of only 0.55%. We have investigated the possibility that the excess shown in Fig. 1*a* may be a systematic effect related to the on- and

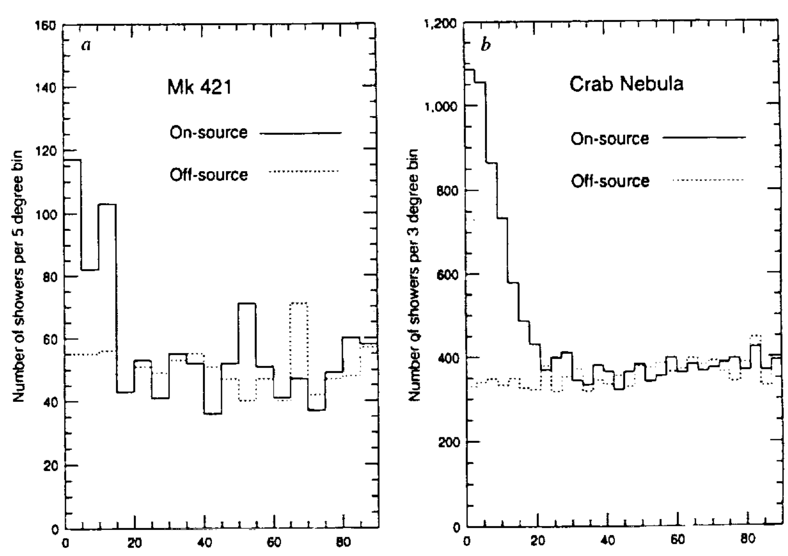

FIG. 1 On- and off-source orientation angle ('alpha') distributions for *a*, Mk 421 and *b*, Crab Nebula. The distributions are for those showers for which the other supercuts selection criteria[16] have been satisfied. The supercuts selection value for alpha is 15°.

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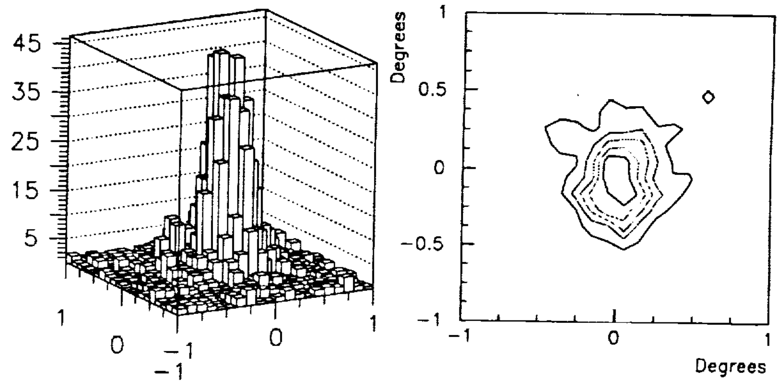

FIG. 2 Maps of the on-source observations for Mk 421 made according to the prescription of ref. 18, Figs 4 and 5. The peak intensity lies within 0.1° of the known location of Mk 421.

off-source star fields but find that control observations of other star fields with similar characteristics show null results when they are subjected to the supercuts analysis.

From the observations a two-dimensional map of the source region[18] may be created. Figure 2 shows the map from the observations of Mk 421. The centre of the field of view corresponds to the known direction of the source. The peak seen is within 0.1° degree of this direction.

Mk 421 is only the second source to be seen by the Cerenkov imaging technique and the first extragalactic source. The power-law energy spectra reported by EGRET (C. E. Fichtel, personal communication) for the active galactic nuclei that it has detected are uniformly hard, with differential photon spectral indices of two or less. For Mk 421 the differential power-law index is estimated as ~1.8 (Y. C. Lin, personal communication on behalf of the EGRET group). The spectral index implied by joining the 100-MeV point with the flux reported here at 0.5 TeV is 2.0. In general, the EGRET spectra, extrapolated to TeV energies, would imply γ-ray intensities greater than that of the Crab Nebula for the brighter sources. Nikishov[11] and Stecker *et al.*[12] have pointed out that absorption of TeV photons by the general background of starlight and infrared photons is severe for sources at $z \approx 1$. Even for a closer source such as 3C 273 at $z = 0.158$, the optical depth at 1 TeV is of order unity. Mk 421, at $z = 0.031$, would be relatively unaffected except at energies above a few TeV. We regard this effect as a possible explanation for the detection of Mk 421 and the failure to detect, as yet, other active galactic nuclei that are brighter than it at GeV energies. But in view of the variability observed for such sources, this cannot yet be confirmed. A preliminary estimate of the spectrum of Mk 421 from our data indicates that the excess is generally confined to energies less than 1.5 TeV. □

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ACKNOWLEDGEMENTS. We thank K. Harris and T. Lappin for help in obtaining these observations. We acknowledge support from the U.S. Department of Energy, NASA, the Smithsonian Scholarly Studies Research Fund and EOLAS, the scientific funding agency of Ireland.

THE ASTROPHYSICAL JOURNAL, 404:206–218, 1993 February 10

SURVEY OF CANDIDATE GAMMA-RAY SOURCES AT TeV ENERGIES USING A HIGH-RESOLUTION CERENKOV IMAGING SYSTEM: 1988–1991

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Received 1992 May 18; accepted 1992 August 17

ABSTRACT

The steady TeV gamma-ray emission from the Crab Nebula has been used to optimize the sensitivity of the Whipple Observatory atmospheric Cerenkov imaging telescope. Using this method, which is of order 20 times more sensitive than the standard method using a simple non-imaging detector, it is possible to detect the Crab Nebula at a significance level in excess of 6 standard deviations (6 σ) in under 1 hr on source (with a corresponding time observing a background comparison region); a source one-tenth the strength of the Crab Nebula can be detected at the 4 σ level after 40 hr on the source (and 40 hr on a background region). A variety of sources have been monitored using this technique over the period 1988–1991, but none were detected apart from the Crab Nebula. Upper limits are presented which in many instances are a factor of 10 below the flux of the Crab Nebula. These upper limits assume steady emission from the source and cannot rule out sporadic gamma-ray emission with short duty cycles.

Subject headings: gamma rays: bursts — ISM: individual (Crab Nebula)

1. INTRODUCTION

Following the reports of the detection of gamma rays from Cygnus X-3 at TeV and PeV energies (Stepanian et al. 1977; Samorski & Stamm 1983), there has been intense observational activity over the entire gamma-ray spectrum above 0.1 TeV. Many other sources have been reported, some of them previously unsuspected of being sites of high-energy activity. These reports, as well as many upper limits on candidate sources, have been the subject of several reviews (Chadwick et al. 1990; Fegan 1990; Weekes 1992). Although there have been significant advances in detector technology, the observational situation is still confused, with conflicting upper limits and detections.

In this paper we report on the observations of a variety of sources with a single high-resolution imaging atmospheric Cerenkov camera; these observations were made over the 3 yr period from 1988 to 1991. The energy threshold was 0.4 TeV with significant sensitivity over the energy range 0.4–4.0 TeV. The efficacy of this technique for the detection of gamma rays from the Crab Nebula has already been reported (Weekes et al. 1989; Vacanti et al. 1991). Because of its ability to discriminate between gamma-ray– and hadron-initiated air showers, the camera achieved a flux sensitivity an order of magnitude better than conventional nondiscriminating telescopes. Although absolute sensitivities with these techniques are imprecise, it is still possible to relate the fluxes to the observed steady flux from the Crab Nebula.

After a brief description of the camera and the observation method used, new observations of the Crab Nebula are reported; selection routines optimized on observations of this source are then used to search for emission from a variety of other objects. These can be divided into two classes: the classical sources which can be confidently predicted to be TeV emitters at some level, and the serendipitous sources in which high-energy particle activity is unexpected. In this 3 yr observing campaign, only upper limits were obtained on sources in both classes.

2. THE HIGH-RESOLUTION CAMERA

An early version of the Cerenkov Imaging Camera using 37 pixels yielded the first clear detection of the Crab Nebula at TeV energies (Weekes et al. 1989). To improve the sensitivity of the technique, the camera was upgraded to a higher resolution version in 1988 May. This system consists of an array of 109 photomultiplier tubes in the focal plane of the Whipple Observatory 10 m optical reflector (Fig. 1). The array consists of 91 2.9 cm photomultiplier tubes in a hexagonal matrix with 0°.25 spacing between centers. These are surrounded by an outer hexagonal ring of 18 5 cm tubes (Fig. 2). The camera is triggered when any two of the inner 91 tubes exceed a preset threshold (40 photoelectrons in a 10 ns interval). The trigger rate varies between 150 and 300 per minute, depending on the reflectivity of the mirrors and the zenith angle of the observation. At the beginning and end of each night's observations, calibration data are obtained using a fast nitrogen flashlamp to generate artificial events for the purpose of determining the relative tube gains. The camera is also artificially triggered to measure the magnitude of the noise in each phototube caused

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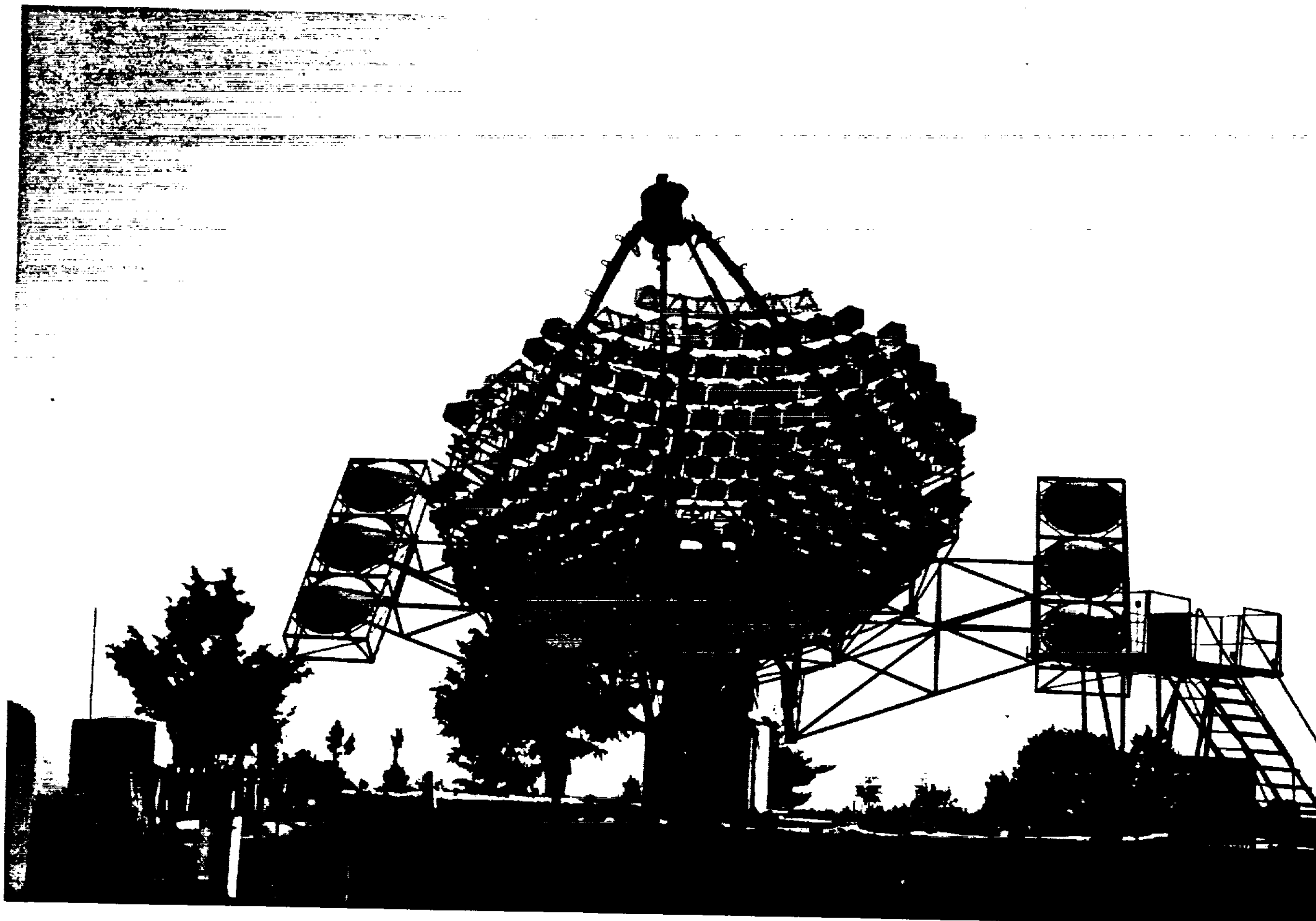

FIG. 1.—The 10 m Reflector on Mount Hopkins, Arizona

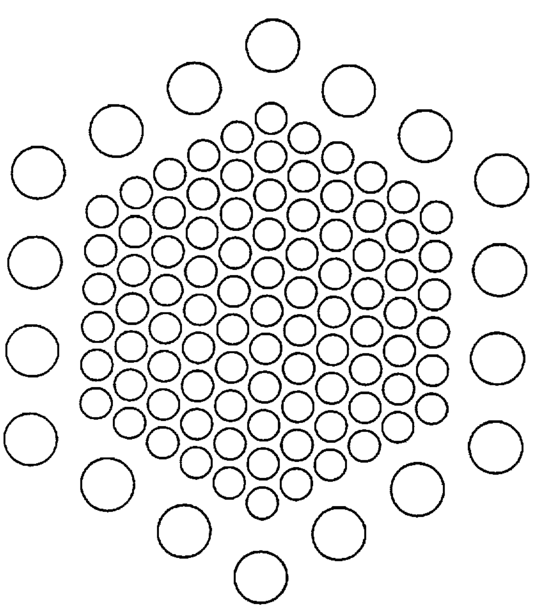

FIG. 2.—Arrangement of the 109 photomultiplier tubes in the focal plane of the 10 m reflector.

by fluctuations in night-sky light. For a more detailed camera description, see Cawley et al. (1990).

The significance levels quoted throughout this paper are calculated assuming Poisson fluctuations only in both ON and OFF counts, i.e., the significance level is given by

$$S1 = (ON - OFF)/(ON + OFF)^{1/2} .$$

It may be argued that this maximizes the significance level by ignoring the possibility of non-Poissonian errors in the data. More elaborate tests on a large subset of the data have shown that the signal fluctuations are only a little greater than Poissonian. As opposed to this possible reduction in significance level, it can also be argued that the above expression actually represents the uncertainty in the strength of the signal being observed, and that the "significance level" associated with the detection of the signal is more realistically represented by

$$S2 = (ON - OFF)/(2 \times OFF)^{1/2} ,$$

which gives the probability that the observed signal is due to a fluctuation in the background; there is a background count in both the ON and OFF counts; hence, the factor of 2 in the denominator (Hillas 1992). *S2* may be considerably larger than *S1* for large differences between ON and OFF counts. At present, though, this modest increase in the calculated significance is largely offset by the small additional non-Poissonian fluctuations. So, by continuing to use the more commonly accepted expression where the variance involves both ON and

OFF counts, we seem to have a simple measure which is fairly close to the real significance, and which facilitates comparison with significance levels in the literature.

3. CRAB NEBULA OBSERVATIONS: 1988–1991

3.1. *Observation of the Crab Nebula, 1988–1989; Azwidth Analysis*

To compare the sensitivity of the high-resolution camera with that of the previous 37 pixel camera, the Crab Nebula was again monitored over the epoch 1988–1989. Results of the analysis of this data have been reported in detail elsewhere (Vacanti et al. 1991); here they are briefly summarized since they form the basis for comparison with data analysis on all other sources.

The 1988–1989 data base consisted of 65 ON/OFF pairs, comprising some 30 hr of ON-source observations. The observations were taken under optimum conditions (clear sky, newly coated mirrors, low zenith angles, etc.). The first analysis was similar to that employed in the initial detection (Weekes et al. 1989) which had given a 9 σ detection based on 60 hr of ON-source observation. Candidate gamma-ray images were selected based on their orientation and shape; at the zenith, this selection rejected 97% of the triggered events. These selection criteria were determined a priori from Monte Carlo simulations of images from hadron and photon-initiated showers. Using the single parameter discriminant Azwidth which combines shape and orientation characteristics of the images, a 20 σ detection was obtained (see Appendix A for definitions of the image parameters such as Azwidth). The results are summarized in Table 1. Clearly, the new camera is more sensitive than the earlier version and the reported detection is confirmed with high significance with the improved detector. The measured flux is 70×10^{-12} cm^{-2} s^{-1} above 0.4 TeV. The flux sensitivity has been improved by a factor of between 2 and 3 over the previous 37 pixel camera.

3.2. *Optimization of the Cerenkov Imaging Technique on the Crab Nebula Data: 1988–1989*

In the above analysis, the individual events were calibrated and prepared for analysis essentially using the methods outlined in previous papers (Weekes et al. 1989; Vacanti et al. 1991). A more efficient method of event treatment was subsequently developed involving more sophisticated handling of pedestals, noise, and gains (Punch et al. 1991). Previously the gamma-ray selection was based principally on the Azwidth parameter using gamma-ray domain boundaries which were predetermined by shower simulations (Hillas 1985). Here a new multiparameter selection is implemented in which the domain boundaries, defined by the shape and orientation parameters, are optimized on a subset of the data, namely the 1988–1989 season of observations on the Crab Nebula. Details of the analysis procedures and cut values are given in Appendix B. With this selection technique ("Supercuts"), the significance of a source detection is increased by a factor of 1.75 over the simpler Azwidth analysis (Punch et al. 1991).

TABLE 1

AZWIDTH-SELECTED ANALYSIS: 1988–1989

Selection	Raw	Azwidth
ON	498426	14622
OFF	493434	11389
Difference	+4992	+3233
σ	+5.0	+20.0

TABLE 2

SUPERCUTS: 1988–1989

Selection	Raw	Shape	Orientation	Supercuts
ON	498426	14218	44099	4452
OFF	493434	11216	40413	1766
Difference	+4992	+3002	+3686	+2686
Excess (σ)	+5.0	+18.8	+12.7	+34.1

The efficacy of Supercuts can be judged from its application to the standard Crab 1988/1989 data base where the significance has been increased to 34 σ. Detailed results are summarized in Table 2. Since Supercuts have been optimized on this set of data, the excess does not have the usual statistical significance. In § 3.3 we show its application to subsequent observations of the Crab Nebula. The same procedure has been used in analyzing data from several other sources (§ 4). In these cases we can derive upper limits (or fluxes) for gamma rays relative to the Crab Nebula flux assuming source spectra similar to that of the Crab; if the source spectrum is significantly different, then the sensitivity may be less.

It has been suggested by Bowden et al. (1992) that the geomagnetic field of Earth may have an adverse effect on the efficiency of the selection procedure used in the imaging technique. Our observations of the Crab Nebula give no indication of this, nor is there support for this effect in our Monte Carlo simulations. The range of transverse magnetic fields covered by our observations of the Crab Nebula is 0.18 G (culmination at zenith angle of 80°) to 0.43 G (at zenith angles of 45°). For these observations there was no indication of any change of the efficiency of the Supercuts procedures with magnetic field. Recently the same Supercuts procedure was shown to be effective in detecting a gamma-ray signal from Markarian 421 (Punch et al. 1992a); in this case the range of magnetic field was from 0.30 to 0.45 G. The range of magnetic fields encountered in the observation of the sources listed in § 4 is from 0.00 to 0.50 G, not far beyond the range encountered in the Crab observations. Monte Carlo simulations (Hillas 1991) show that the overall effect of the geomagnetic field is that of a slight increase in the effective energy of the selected gamma rays with the transverse magnetic field but that there is negligible effect on the shower parameters. Hence the effect of the magnetic field is slight and within the range of uncertainties (a factor of 1.5) of the absolute energy threshold of the telescope which is calculated for a geomagnetic field of 0.25 G.

3.3. *Application to the Crab Nebula Observations: 1988–1991*

Applying Supercuts "a posteriori" to the 1988–1989 data base (from which it is derived), the detection level has been increased to 34 σ. The same Supercuts selection is now applied ("a priori") to the subsequent Crab observations taken in 1989–1990 and 1990–1991. Detailed results are summarized in Table 3 together with the total for all three observing seasons (Lang et al. 1991).

The following points should be noted:

1. The signal is seen each year with no evidence for variability; the decline in statistical significance is consistent with the increase in energy threshold due to the degradation in mirror reflectivity.
2. The overall detection (1988–1991) does not have full sig-

TABLE 3

SUPERCUT ANALYSIS

Selection	Raw	Shape	Orientation	Supercuts
Epoch: 1988–1989; Time: 1808 minutes; Mean Elevation: 69.8				
ON	498426	14218	44099	4452
OFF	493434	11216	40413	1766
Difference	+4992	+3002	+3686	+2686
σ	+5.0	+18.8	+12.7	+34.1
Rate (average) per minute	272.9			
Epoch: 1989–1990; Time: 1232 minutes; Mean Elevation: 72.0				
ON	282137	7331	23635	2290
OFF	280249	5832	21688	904
Difference	+1888	+1499	+1947	+1386
σ	+2.5	+13.1	+9.1	+24.5
Rate (average) per minute	227.5			
Epoch: 1990–1991; Time: 1065 minutes; Mean Elevation: 73.0				
ON	187475	5198	16089	1488
OFF	185287	4494	14855	669
Difference	+2188	+704	+1234	+819
σ	+3.6	+7.1	+7.0	+17.6
Rate (average) per minute	174.0			
Epoch: 1988–1991 (all); Time: 4105 minutes; Mean Elevation: 71.3				
ON	968038	26747	83823	8230
OFF	958970	21542	76956	3339
Difference	+9068	+5205	+6867	+4891
σ	+6.5	+23.7	+17.1	+45.5

nificance associated with 45.5 σ as it includes the optimized result for 1988–1989.

3. The signal is seen strongly in the raw data; the hardware trigger, which demands that any two of the inner 91 PMTs exceed a preset threshold level, favors narrow images where the light is concentrated within a small number of pixels; a similar amount of light in a more diffuse hadron-like image will not so readily trigger the system, thus resulting in a hardware trigger bias toward narrow, gamma-ray like, images.

4. The signal is seen after software processing with selection both by shape and orientation and in a combined selection by shape *with* orientation as predicted by simulations.

5. With Supercuts, a signal has been isolated that is 59% gamma rays, 41% background; the gamma-ray signal is detected at a rate of 1.2 per minute and the number of gamma rays recorded from this source is 4891.

6. In a recent paper (Akerlof et al. 1991a) it is shown that the source location capability (angular resolution) of the technique for a source of this strength is a few arcminutes (similar to EGRET on the *Gamma Ray Observatory*)—when the Crab Nebula was deliberately displaced from the center of the field of view of the telescope, an unambiguous signal was detected at the expected celestial coordinates, thus eliminating the possibility of any symmetry-induced biases in the original on-axis detections.

7. The signal is about 0.5% of the cosmic-ray background; for a conventional camera which triggered on cosmic-ray showers, this might be about 0.2% of the background.

The distribution of the excesses per run calculated after the application of Supercuts was examined (the average run duration was 28 minutes). No evidence for variability was found on this time scale. A search has also been made for evidence of periodic emission at the known Crab Pulsar period. The data base for this analysis was expanded from that used above since it was possible to include tracking observations under non-optimum conditions. The expanded data base covered 7390 minutes. As reported previously (Weekes et al. 1989; Vacanti et al. 1991), no evidence is found for steady pulsar emission, and an upper limit is estimated at 1.4×10^{-12} cm^{-2} s^{-1} ($E > 0.4$ TeV), i.e., less than 2% of the unpulsed nebular emission. The resulting light curve for the 3 yr of Supercuts data folded at the Crab period using the pulsar ephemeris (Lyne & Pritchard 1991) is shown in Figure 3. In an examination of individual runs for periodic emission, one scan did show some indication of a Crab-like light curve (Punch et al. 1992b); the narrow peak of the light curve was found to be within 0.03 of the expected phase. This scan was a tracking run taken on 1991 January 11, starting at 0402 UT and lasting for 29 sidereal minutes. The probability that this peak was due to a random fluctuation was estimated at 0.7% (taking all tests on the complete data set into consideration). As evidence for TeV gamma-ray pulsar emission, the significance of this isolated scan, in the absence of a clear a priori hypothesis, is not compelling.

4. APPLICATION OF THE CERENKOV IMAGING TECHNIQUE TO OTHER SOURCES

In Table 4 we summarize the flux levels and upper limits for a total of 27 objects monitored using the high-resolution camera between 1988 May and 1991 June (Akerlof et al. 1991b; Reynolds et al. 1991b). Only one source, the Crab Nebula, is presented as a positive detection; for all the other objects we present upper limits for steady, unpulsed emission. The 3 σ upper limits are based on the Supercuts analysis; here $\sigma = (\mathrm{ON} + \mathrm{OFF})^{1/2}$. The collection area ($3.5 \times 10^8$ cm^2) is estimated from simulations. Upper limits relative to the Crab Nebula are also quoted (in millicrabs) where an integral source spectral index of -1.4 is assumed (i.e., similar to that of the Crab Nebula). For some of these objects, upper limits for pulsed emission are also discussed in the text below. Three sigma upper limits are given in all cases, and there is an uncer-

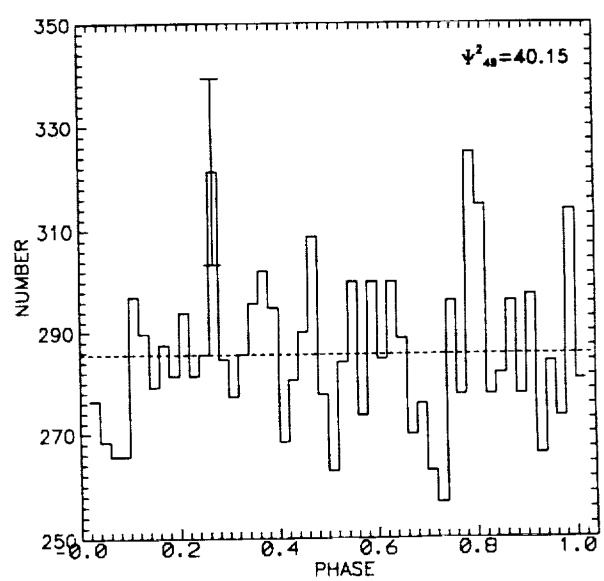

FIG. 3.—Light curve for the Crab pulsar after Supercuts. Phase zero corresponds to the radio main pulse.

TABLE 4

UPPER LIMITS FOR STEADY, UNPULSED EMISSION

Source	Class	Time (minutes)	Elev	Energy (TeV)	Flux ($<10^{-12}$ cm^{-2} s^{-1})	Flux mCrab
Standard Candle						
Crab Nebula	Plerion	1808	71°	0.4	70[a]	...
Extended Classical Sources						
Diffuse Background	...	300	90	0.4	[b]	...
Galactic Plane	...	720	90	0.4	[c]	...
Taurus GMC	...	288	79	0.5	18	...
Discrete Classical Sources						
SS 433	Plerion	191	50	0.55	18	400
3C 58	Plerion	403	53	0.55	11	250
PSR 0656	Plerion	84	31	1.0	34	1750
2CG 135	MeV/GeV	140	59	0.55	16	350
Geminga	MeV/GeV	570	61	0.4	8.9	130
GeV-A	GeV	214	61	0.45	32	530
3C 273	AGN/GeV	1586	54	0.48	5.1	90
3C 279	AGN/GeV	453	46	0.40	14	200
NGC 4151	AGN/MeV	1132	74	0.50	3.6	70
M87	Radiogalaxy	745	65	0.40	7.0	100
SN 1990B	Supernova	223	66	0.45	11	180
SN 1991T	Supernova	111	59	0.55	14	310
Binaries and Pulsars						
Cyg X-3	Binary	2922	69	0.4	3.5	50
Her X-1	Binary	1404	72	0.48	3.3	60
4U 0115+63	Binary	366	56	0.55	12	260
V0332+53	Binary	352	64	0.40	14	200
Sco X-1	Binary	635	40	0.75	12	420
4U 2129+47	Binary	336	63	0.55	11	250
1E 2259+58	Binary	362	65	0.55	11	250
AM Her	Cataclysmic variable	748	63	0.55	5.5	130
PSR 0950+08	Pulsar	499	63	0.40	8.3	120
PSR 0355+54	Pulsar	2032	62	0.45	4.0	70
PSR 1855+09	Pulsar	305	58	0.60	9.5	240

[a] Detection flux level rather than upper limit.
[b] $I_\gamma/I_h < 1.1 \times 10^{-3}$ (see text).
[c] $<1.9 \times 10^{-9}$ cm^{-2} s^{-1} rad^{-1}.

tainty factor of 1.5 in the absolute value of energy threshold and collection area. In cases where there is apparent conflict with quoted fluxes from previous detections, it must be borne in mind that these upper limits are for steady emission of TeV gamma rays; for transient sources, such upper limits may not be relevant unless coupled with a long observing campaign. In Tables 5 and 6 we present details of the observations on the sources.

The source catalog is divided into two categories: "classical" sources and binaries and pulsars. Each source is discussed briefly below.

4.1. *Classical Sources*

Much of the excitement in VHE gamma-ray astronomy has come from the detection of the episodic periodic galactic sources. This has led to the relative neglect of a wide spectrum of "classical" sources. These are characterized by the fact that emission of TeV gamma rays is expected at some level, based on theoretical predictions or on observations at longer wavelengths. The predicted level is uncertain and may be below the level achievable with the present generation of detectors; here we report observations on these sources with the Whipple high-resolution camera.

Diffuse Background (extended source).—There are no detailed theoretical predictions of the diffuse background at TeV energies but, by extrapolation of measurements at MeV-GeV energies, it is expected to be about 10^{-5} of the cosmic-ray background at comparable TeV energies. The atmospheric Cerenkov imaging technique offers the first possibility of measuring the flux because of the ability of the technique to discriminate gamma-ray showers from those caused by hadrons. Because the flux is diffuse, only the shape parameter, Width, can be used. Simulations show that a range of Width from 0°.04 to 0°.12 results in the detection of the diffuse gamma-ray component with 71% efficiency. Based on 5 hr of observation at the zenith, the percentage of detected events in this range is determined (3.8%); a high fraction of these events come from local cosmic rays passing through the phototubes. This fraction was measured (with camera closed) and found to be 2.96% of the total. The percentage of true cosmic-ray shower events within the gamma-ray domain is then 0.84% $\pm$ 0.13%. Allowing for the triggering inefficiency of background showers compared to gamma-ray showers and the collection area for gamma rays, an upper limit (>0.4 TeV) $I_{\rm gamma}/I_{\rm hadron} < 1.1 \times 10^{-3}$ is derived.

Galactic Plane (extended source).—There have been previous

TABLE 5

OBSERVATION SUMMARY: DISCRETE CLASSICAL SOURCES

Selection	Raw	Shape	Orientation	Supercuts	Selection	Raw	Shape	Orientation	Supercuts
SS 433; Epoch: 1990					3C 273; Epoch: 1989 1991				
ON	32535	1769	2894	280	ON	320093	10869	41389	1674
OFF	32355	1835	3018	279	OFF	319659	10794	40963	1580
Difference	+180	−66	−124	+1	Difference	+434	+75	+426	+94
σ	+0.7	−1.0	−1.6	+0.0	σ	+0.5	+0.5	+1.5	+1.6
3C 58; Epoch: 1990–1991					3C 279; Epoch: 1989				
ON	65248	3221	5737	484	ON	110969	6552	10528	975
OFF	64598	3036	5723	446	OFF	111728	6443	10549	1001
Difference	+650	+185	+14	+38	Difference	−759	+109	−21	−26
σ	+1.8	+2.3	+0.1	+1.2	σ	−1.6	+1.0	−0.1	−0.6
PSR 0656; Epoch: 1991					NGC 4151; Epoch: 1990–1991				
ON	7721	1436	777	191	ON	201063	2417	15211	439
OFF	7485	1271	808	200	OFF	200812	2455	15187	387
Difference	+236	+165	−31	−9	Difference	+251	−38	+24	+52
σ	+1.9	+3.2	−0.8	−0.5	σ	+0.4	−0.5	+0.1	+1.8
2CG 135; Epoch: 1990 Oct–Nov					M87; Epoch: 1989				
ON	22976	791	2022	130	ON	194713	4386	15997	688
OFF	22854	782	1995	118	OFF	194869	4424	15927	634
Difference	+122	+9	+27	+12	Difference	−156	−38	+70	+54
σ	+0.6	+0.2	+0.4	+0.8	σ	−0.2	−0.4	+0.4	+1.5
Geminga; Epoch: 1989 Dec–1990 Jan					SN 1990; Epoch: 1990 Jan–Feb				
ON	121523	3807	9380	649	ON	46990	843	3598	135
OFF	122027	3756	9412	601	OFF	47373	816	3680	138
Difference	−504	+51	−32	48	Difference	−383	+27	−82	−3
σ	−1.0	+0.6	−0.2	1.4	σ	−1.2	+0.7	−1.0	−0.2
GeV-A; Epoch: 1990 May					SN 1991T; Epoch: 1991 May				
ON	45143	1150	3827	198	ON	17420	403	1387	50
OFF	44986	1122	3723	184	OFF	17583	398	1458	63
Difference	+157	+28	+104	+14	Difference	−163	+5	−71	−13
σ	+0.5	+0.5	+1.2	+0.7	σ	−0.9	+0.2	−1.3	−1.2

indications (of low statistical significance) of a broad enhancement at TeV energies near $|b| \sim 5°$ and a dip inside $|b| < 1°5$ (where b is the Galactic latitude) (Fomin, Vladimirsky, & Stepanian 1977; Weekes, Helmken, & L'Heurcux 1979; Dowthwaite et al. 1985). Two six hour drift-scans across the plane gave an upper limit of 1.9×10^{-9} cm^{-2} s^{-1} rad^{-1} with energy 0.4 TeV for a source region $+5°$ of galactic latitude using shape selection only; this agrees with limits reported previously for $E > 0.9$ TeV (Reynolds et al. 1990).

Taurus Giant Molecular Cloud (*extended source*).—There have been several predictions of VHE emission from GMC's. Because of their large extent they are not ideally suited to observation with narrow beam atmospheric Cerenkov telescopes. However, some models indicate that the diffuse fluxes from such sources may be within the sensitivity of the Cerenkov imaging technique (e.g., Aharonian 1990). Here, the first upper limit on the Taurus GMC is reported as 1.8×10^{-11} cm^{-2} s^{-1} above 0.5 TeV where gamma-ray event selection has been limited to shape (Width) only. The energy spectrum is plotted in Figure 4.

Plerions.—A plerion is a supernova remnant with a centrally filled morphology, similar to the Crab Nebula. Three other plerions were monitored, namely SS 433, 3C 58 and PSR 0656; none of these would be expected to have the intensity of the Crab Nebula. The results of these observations are given in

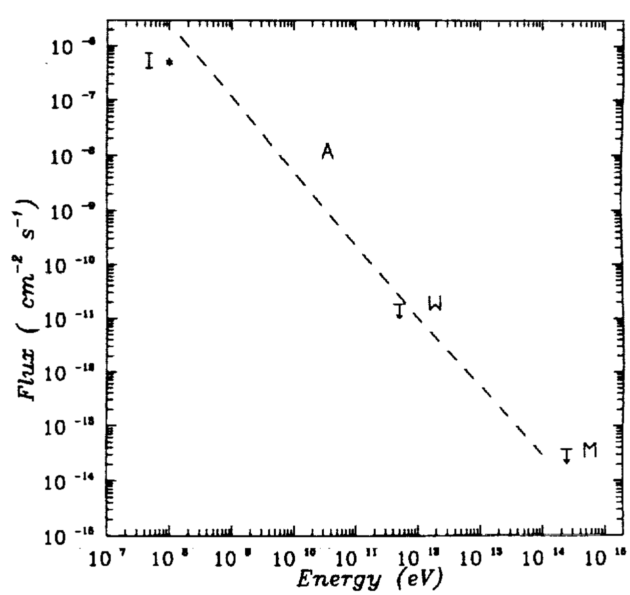

FIG. 4.—Detection, upper limits, and predicted spectrum for the Taurus Giant Molecular Cloud. I: Issa & Wolfendale (1981); A: Aharonian (1990); M: Matthews (1990); W: this paper.

TABLE 6

Observation Summary: Binaries and Pulsars

Selection	Raw	Shape	Orientation	Supercuts
Cyg X-3; Epoch: 1988–1990				
ON	651806	16190	53628	2548
OFF	653338	15954	53493	2600
Difference	−1532	+236	+135	−52
σ	−1.3	+1.3	+0.1	−0.7
Her X-1; Epoch: 1988–1991				
ON	284397	3256	25056	523
OFF	282976	3387	24852	542
Difference	+1421	−131	+204	−19
σ	+1.9	−1.6	+0.9	−0.6
4U 0115+63; Epoch: 1988 Dec				
ON	95995	3066	8112	486
OFF	95609	3200	8044	520
Difference	+386	−134	+68	−34
σ	+0.9	−1.7	+0.5	−1.1
V 0332+53; Epoch: 1988				
ON	88569	3254	7531	575
OFF	89033	3433	7417	549
Difference	−464	−179	+114	+26
σ	−1.1	−2.2	+0.9	+0.8
Sco X-1; Epoch: 1990				
ON	108442	9361	10493	1497
OFF	108406	9326	10602	1453
Difference	+36	+35	−109	+44
σ	+0.1	+0.3	−0.7	+0.8
4U 2129+47; Epoch: 1990				
ON	56145	2113	4889	332
OFF	55684	2041	4742	316
Difference	+461	+72	+147	+16
σ	+1.4	+1.1	+1.5	+0.6
1E 2259+58; Epoch: 1990				
ON	59246	2478	4889	377
OFF	58692	2355	4934	378
Difference	+554	+123	−45	−1
σ	+1.6	+1.8	−0.4	−0.0
AM Her; Epoch: 1990–1991				
ON	120020	2508	9778	423
OFF	119968	2587	9820	410
Difference	+52	−79	−42	+13
σ	+0.1	−1.1	−0.3	+0.4
PSR 0905; Epoch: 1988–1991				
ON	137497	2585	10985	416
OFF	137154	2551	11148	419
Difference	+343	+34	−163	−3
σ	+0.6	+0.5	−1.1	−0.1
PSR 0355; Epoch: 1988–1991				
ON	455934	10201	37548	1572
OFF	456386	10487	37049	1650
Difference	−452	−286	+499	−78
σ	−0.5	−2.0	+1.8	−1.4
PSR 1855+09; Epoch: 1988–1991				
ON	47231	1372	3931	187
OFF	47919	1476	4009	223
Difference	−688	−104	−78	−36
σ	−2.2	−1.9	−0.8	−1.8

Table 4. The upper limit derived for SS 433 is F (>0.55 TeV) = 1.8×10^{-11} cm^{-2} s^{-1}; previously reported upper limits were F (>1 TeV) < 1.0×10^{-10} cm^{-2} s^{-1} (Gorham, Stenger, & Weekes 1982) and F (>0.4 TeV) < 2.1×10^{-10} cm^{-2} s^{-1} (Bowden et al. 1991a).

2CG 135+1 (MeV/GeV source).—This was first reported as a gamma-ray source by the *COS-B* experiment. The upper limit (Table 4) is based on the assumption that the source is at the center of the error circle (of radius 1°) and has a Crab-like spectrum.

Geminga (MeV/GeV source).—The high energy gamma-ray source 2CG 195+4 is the second strongest source in the *COS B* catalog. A 59 s periodicity was reported on the basis of *SAS 2* data (Thompson et al. 1977) but not confirmed by *COS B* (Masnou et al. 1981; an earlier confirmation was withdrawn after reconsidering the statistics involved). Low significance detections at TeV energies have been claimed by two groups, but both depend on the disputed 59 s periodicity (Zyskin & Mukanov 1985; Kaul et al. 1985). The claimed pulsed fluxes were 5×10^{-11} cm^{-2} s^{-1} (E > 1 TeV) and 9.5×10^{-12} cm^{-2} s^{-1} (E > 6 TeV), respectively. This much-studied source was an object of high priority for observations using the high-resolution camera. A large data base was accumulated, and results from the complete analysis will be presented elsewhere. Results from a subset of the data base are presented in Table 5; there is as yet no evidence for TeV gamma-ray emission of 8.9×10^{-12} cm^{-2} s^{-1} (E > 0.4 TeV), i.e., less than 13% of the flux of the Crab Nebula, is derived.

GeV-A (GeV source).—The Japanese aircraft experiment (Enomoto et al. 1990a) reported the apparent detection of a number of sources with energies >40 GeV. The strongest of these (source "A") was monitored using the 10 m Cerenkov Imaging telescope in 1990 May with null results. Because of positional uncertainty, the upper limit quoted in Table 4 has been based on shape discrimination only. The energy spectrum is shown in Figure 5. A subsequent flight of the aircraft experiment failed to confirm this source; the original detection may have been due to a fluctuation in the diffuse gamma-ray background (Enomoto et al. 1990b).

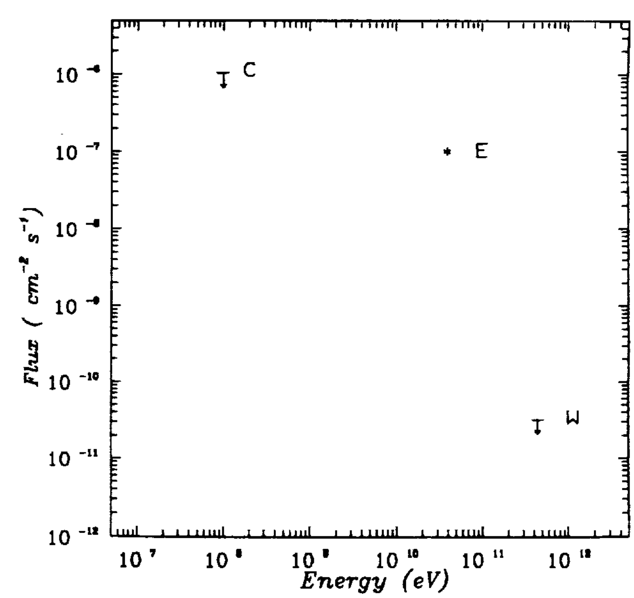

Fig. 5.—Detection and upper limits for GeV-A. C: Bignami & Hermsen (1983); E: Enomoto et al. (1990a); W: this paper.

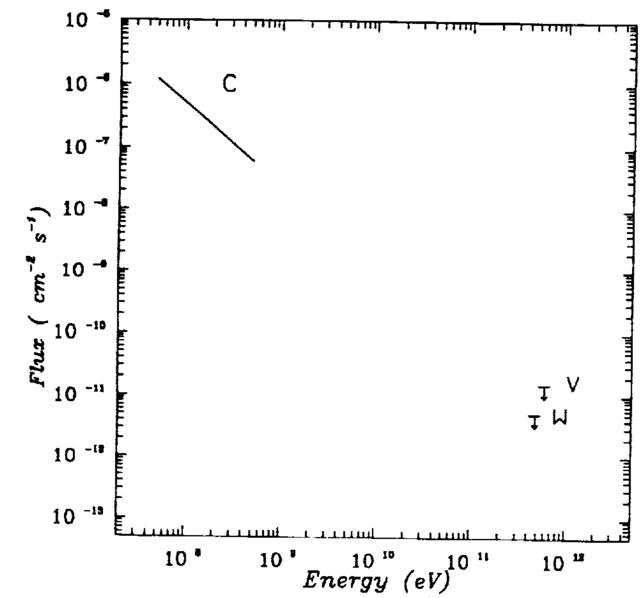

FIG. 6.—Energy spectrum for the quasar 3C 273. C: Swanenburg et al. (1978); V: Vacanti et al. (1990); W: this paper.

3C 273 (*MeV/GeV source, quasar*).—Previously reported upper limits (Vacanti et al. 1990) are updated (Table 4 and Fig. 6).

3C 279 (*MeV/GeV source, quasar*).—This is reported as a new variable source in 1991 May by EGRET on the *Compton Gamma-Ray Observatory* (Hartman et al. 1992). Observations reported previously (Vacanti et al. 1990) are reanalyzed with Supercuts and a new upper limit reported in Table 4 and Figure 7. These observations were made in the spring of 1989, prior to the launch of the *GRO*. The source was not in a high state of activity at that time (Webb et al. 1990; Hartman et al. 1992).

NCC 4151 (*MeV source, AGN*).—Observations taken in 1990–1991 at high elevation give a strong upper limit (Table 4).

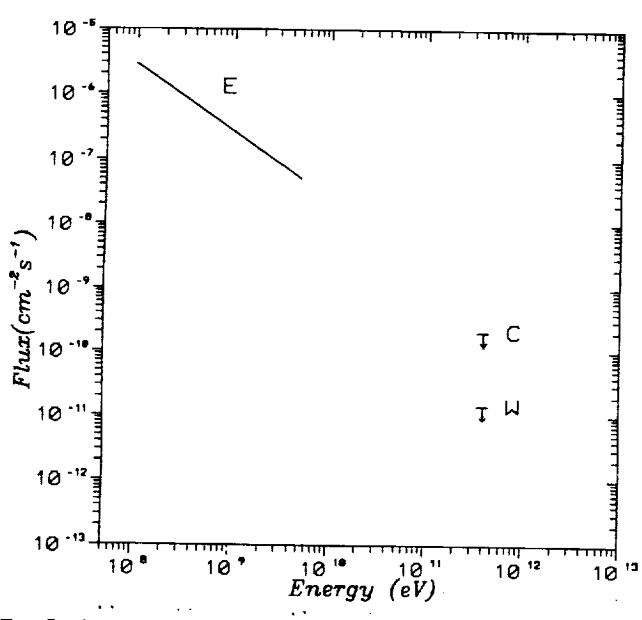

FIG. 7.—Energy spectrum for the quasar 3C 279. E: Hartman et al. (1992); C: Cawley et al. (1985); W: this paper.

M87 (*radio galaxy*).—This strong radio galaxy with conspicuous jet has been predicted to be a source of TeV gamma rays (Rieke & Weekes 1969); no evidence for gamma-ray emission is found in these observations (Table 4).

SN 1990B, SN 1991T (*extragalactic supernovae*).—These two relatively bright supernovae were observed soon after initial outburst; there is no evidence for TeV gamma-ray emission. SN 1991T was the brightest Type Ia supernovae seen since 1972; it was a target of opportunity for the *Compton GRO*, but no gamma-ray emission was seen at any wavelength.

4.2. *Binaries and Pulsars*

TeV emission has been claimed from many X-ray binaries, radio pulsars, and cataclysmic variables (for recent reviews, see Chadwick et al. 1990; Fegan 1990; Weekes 1992). In almost all cases the reported signal is periodic and episodic with the episodes lasting from minutes to days. In most cases the signals do not have the properties expected of gamma-ray showers. The Whipple Observatory high-resolution imaging telescope was used to observe a selection of these objects; detailed reports on some of these sources have been published elsewhere (Cawley et al. 1991; Macomb et al. 1991; Reynolds et al. 1991a; O'Flaherty et al. 1991).

Observations were in two forms: ON/OFF as used for steady sources and tracking (ON only) when weather conditions were less than optimum. The latter were used to supplement the data base in searching for periodicity. All observations were made between 1988 May and 1991 June. Energy threshold and flux limits are quoted assuming an energy spectrum similar to that of the Crab Nebula. No statistically significant signals were seen from any of the sources, either in terms of a net excess or a steady or episodic periodic signal. Upper limits for the net excess are quoted in Table 4 for the sources observed; in the absence of definite predictions, it is difficult to quote meaningful upper limits from the periodic searches. For the radio pulsars the limits are based on an assumed 10% duty cycle with all observations phase-linked.

Cyg X-3 (*binary*).—TeV gamma-ray emission was detected by several groups from this source at relatively low statistical significance during the 1970s and early 1980s (see review in Weekes 1988). The emission was typically modulated at the 4.8 hr orbital period with an average flux of 2×10^{-10} cm^{-2} s^{-1} near phase 0.2 or 0.65. In recent years, most searches have concentrated on the possible periodic component in the gamma-ray signal and there have been no recent reports of a net excess from this source at TeV energies. There have been a number of reports by the Durham group of the detection of a 12.59 msec periodicity (e.g., Bowden et al. 1991b). This has been confirmed by the Adelaide group (Gregory et al. 1990), but only upper limits have been reported by the Whipple, Haleakala, and Tata groups (O'Flaherty et al. 1991; Resvanis et al. 1987; Bhat, Ramana Murthy, & Vishwanath 1988). Here we report an upper limit of 3.5×10^{-12} s^{-1} for unpulsed gamma-ray emission, which is an order of magnitude below the fluxes observed in the early 1980s when the latter are averaged over the complete 4.8 hr cycle. We find no evidence for any modulation at either the 4.8 hr orbital period or the 12.59 ms pulsar period.

Her X-1 (*binary*).—This is one of the best observed and best established binary sources with all reports based on the observation of episodic outbursts of periodic emission. A summary of 6 yr of observations of this source by the Whipple telescope has been published elsewhere (Reynolds et al. 1991a). In this

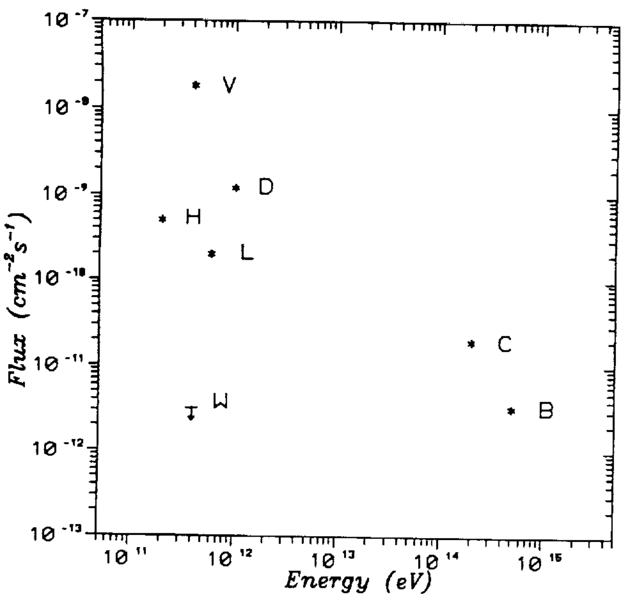

FIG. 8.—Detections and upper limits for the X-ray binary Hercules X-1. D: Dowthwaite et al. (1984); B: Baltrusaitis et al. (1985); H: Resvanis et al. (1988); L: Lamb et al. (1988); C: Dingus et al. (1988); V: Vishwanath et al. (1989); W: this paper.

report the data base has been extended by another year of observations with the high-resolution camera; again no significant emission is detected. An upper limit to the steady emission is found at a level of 3.3×10^{-12} cm^{-2} s^{-1}, or 1/20th that of the Crab Nebula (Fig. 8). This may be contrasted with the peak flux of 1.2×10^{-9} cm^{-2} s^{-1} during the discovery burst (Dowthwaite et al. 1984) which was one of the strongest outbursts of VHE gamma rays ever recorded. It would appear that this source is capable of changing its level of VHE gamma-ray activity by two to three orders of magnitude.

4U 0115+63 (binary).—TeV emission modulated at the pulsar period of 3.6 s was first detected by the Durham group (Chadwick et al. 1985) with a flux of 7×10^{-11} cm^{-2} s^{-1} ($E > 1$ TeV). This was confirmed by the same group at a flux of 4.4×10^{-10} cm^{-2} s^{-1} ($E > 0.4$ TeV) (Brazier et al. 1990a). In both instances, no variation in signal strength was found which suggests that 4U 0115+63 is a source of continuous TeV radiation with a flux a factor of 6 larger than the steady flux from the Crab Nebula. Analysis of 4 yr of data on 4U 0115+63 taken using the imaging gamma-ray telescope at the Whipple Observatory is reported in detail elsewhere (Macomb et al. 1991). Here we report an upper limit for steady emission of 1.2×10^{-11} cm^{-2} s^{-1} ($E > 0.55$ TeV) based on 16 ON/OFF 23 minute scans taken with the high-resolution camera on 6 nights in 1988 December 1–12.

V0332+53 (binary).—This is a transient X-ray emitter with a 4.4 s pulsar period. TeV emission has not been observed from this source, and upper limits have previously been presented (Cawley et al. 1987). Here we report a more stringent upper limit for steady gamma-ray emission of 1.4×10^{-11} cm^{-2} s^{-1} ($E > 0.4$ TeV).

Sco X-1 (binary).—There have been several claims for UHE emission from this X-ray binary (Matano et al. 1990; Gupta et al. 1991) and one report of VHE emission (Brazier et al. 1990b). The latter corresponds to a steady flux of 1.2×10^{-10} cm^{-2} s^{-1} ($E > 0.3$ TeV) with weak evidence for modulation at the 0.787 day orbital period. Here we report an upper limit of 1.2×10^{-11} cm^{-2} s^{-1} ($E > 0.75$ TeV) based on 10.5 hr of data.

4U 2129+47.—This binary was suggested as a potential TeV emitter by Cheng (1990); there have been no previous reports of gamma-ray emission from this source. No net excess was found, and the upper limit is presented in Table 4. The data were also tested for modulation at the 5.2 hr binary orbital period (McClintock et al. 1982). No evidence for modulation was found, but phase coverage was incomplete.

1E 2259+58 (binary).—A time-averaged flux of 2×10^{-10} cm^{-2} s^{-1} ($E > 0.4$ TeV) was reported from this source by the Durham group based on observations made in 1988 October (Brazier et al. 1990c). The reported flux was modulated at a period close to the second harmonic of the X-ray pulsar period (i.e., close to 3.5 s). Upper limits for this source have been reported previously (see Cawley et al. 1991 for details). In particular, an upper limit for pulsed emission of 2.4×10^{-11} cm^{-2} s^{-1} ($E > 0.6$ TeV) was reported for data taken over the same time span as the Durham observations. The data discussed here were taken in 1990–1991, and again no periodicity was found in the expanded data base which included an extra 350 minutes. An upper limit to the periodic gamma-ray signal (assuming a sinusoid light curve) was derived from 300 minutes of data which were phase-linked over 14 days, similar to that in the original discovery; this limit was 1.4×10^{-11} cm^{-2} s^{-1} or 310 millicrab (Fig. 9).

AM Her (cataclysmic variable).—VHE gamma-ray emission has been reported from two cataclysmic variables: AM Her (Bhat et al. 1990a) and AE Aqr (Bowden et al. 1991c; Meintjis et al. 1991). The time-averaged flux reported for the magnetic white-dwarf binary system AM Her was 5.6×10^{-11} cm^{-2} s^{-1} ($E > 2$ TeV). The flux was modulated at the 3.1 hr binary orbital period. Observations using the high-resolution Cerenkov imaging camera in 1990–1991 showed no evidence for TeV emission from this source, and an upper limit was found which is a factor of 10 below the reported flux for a lower threshold energy.

PSR 0950+08 (pulsar).—There have been some claims of

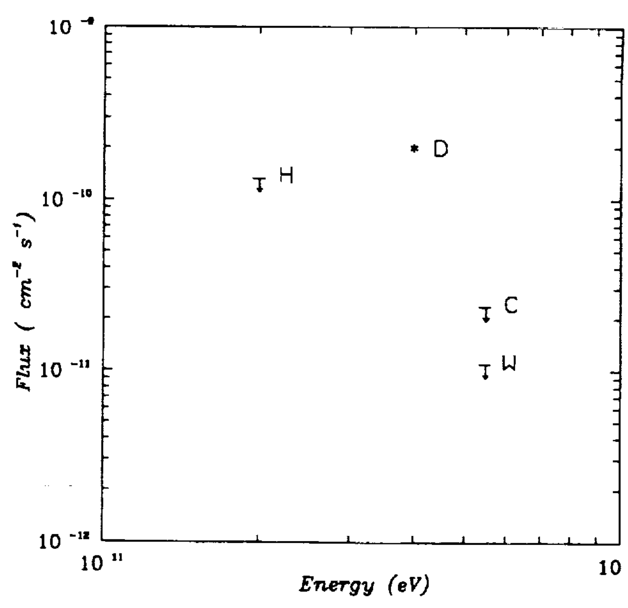

FIG. 9.—Detection and upper limits for the X-ray binary 1E 2259+586. H: Weeks (1990); B: Brazier et al. (1990c); C: Cawley et al. (1991); W: this paper.

TeV emission from this 0.253 s radio pulsar, but the significances were low and in some instances the effects vanished following reanalysis with improved ephemerides (see Weekes 1988 for references and details). An upper limit for unpulsed emission based on ON/OFF data is presented in Table 4. When this data is combined with an extra 917 minutes of tracking data, no evidence for periodic emission is found and the upper limit to steady periodic emission with a 10% duty cycle is 1.4×10^{-12} cm^{-2} s^{-1} for $E > 0.4$ TeV (a relative flux of 20 millicrab).

PSR 0355+54 (pulsar).—This 0.156 s radio pulsar is characterized by occasional large glitches, similar to those seen in the Vela pulsar (the strongest 100 MeV source in the *COS B* catalog). A modulated gamma-ray flux of 8.6×10^{-12} cm^{-2} s^{-1} ($E > 1.3$ TeV) was reported from this source (Bhat et al. 1990b) for data taken in 1987 December (two large radio glitches were observed during 1986). No evidence for emission was found using the high-resolution camera, and an upper limit for unpulsed emission is given in Table 4. From a total of 2328 minutes of tracking data we derive an upper limit to steady periodic emission with a 10% duty cycle of 1.1×10^{-12} cm^{-2} s^{-1} for $E > 0.45$ TeV (Fig. 10). This corresponds to a relative flux of 20 millicrab.

PSR 1855+09 (msec pulsar).—This 5.4 ms pulsar is nearby (400 pc from the solar system) and is predicted to give a strong TeV flux. It was first claimed as a source of TeV gamma-ray emission by the Potchefstroom group (de Jager et al. 1990) although the overall significance level was marginal (5%). The estimated peak flux was 1.6×10^{-10} cm^{-2} s^{-1} for $E > 2$ TeV (both flux and threshold are approximate as they are not explicitly stated in this form in de Jager et al. 1990). The Durham group have reported a peak flux of 5×10^{-10} cm^{-2} s^{-1} ($E > 0.4$ TeV) pulsed at the second harmonic of the radio period (Bowden et al. 1991d). No evidence for gamma-ray emission was found using the Cerenkov Imaging detector. A total of 419 minutes of tracking data gives an upper limit to steady periodic emission of 3.4×10^{-12} cm^{-2} s^{-1} ($E > 0.6$ TeV), or a relative flux of 90 millicrab.

5. CONCLUSIONS

An optimized data selection procedure has been derived based on one season of observations of the Crab Nebula; this increases the flux sensitivity of the Whipple Imaging detector by a factor of about 20 compared with a nonimaging detector. A factor of order 4 was gained in the original 37 pixel system; this was followed by a factor of order 3 in going to the high-resolution camera, with a subsequent factor of order 1.7 gained through optimization of software selection procedures. The selection is verified by application to subsequent observations of the Crab Nebula. Using this selection, a signal can be seen from the Crab Nebula at a level in excess of 6 σ (on average) in 1 hr of observation on the source (with a corresponding time observing a background region); a source one-tenth the strength of the Crab Nebula can be detected at the 4 σ level in 40 hr on the source (and 40 hr on a background region). The same selection has been applied to the analysis of observations of a number of other sources; only upper limits are found.

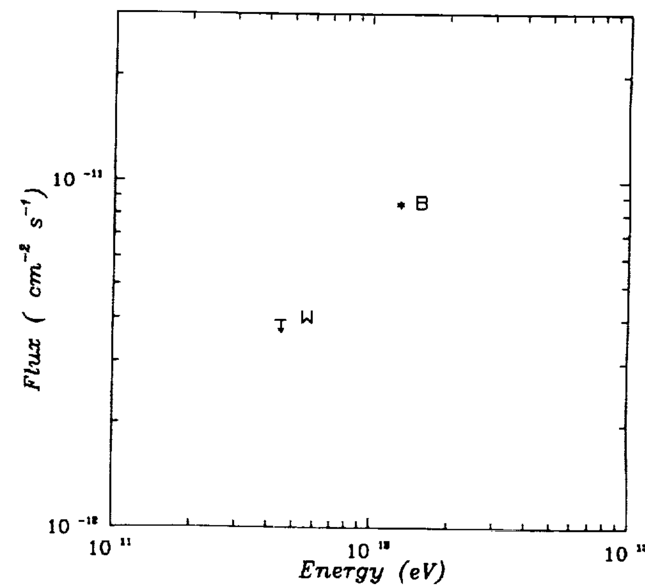

FIG. 10.—Detection and upper limit for the pulsar PSR 0355+54. B: Bhat et al. 1990b; W: this paper.

A second telescope of 11 m diameter has now been deployed at a distance of 120 m from the original 10 m reflector on Mount Hopkins. The capability of recording stereoscopic images of the Cerenkov flashes using these two telescopes, coupled with a lower energy threshold, should give rise to an order-of-magnitude increase in the flux sensitivity for showers imaged in both telescopes (Akerlof et al. 1991c). This more sensitive detector system will be used to carry out deeper searches for TeV emission from the sources discussed in this paper.

We acknowledge the assistance of Kevin Harris and Teresa Lappin in making the observations. We also acknowledge the support of the U.S.D.O.E., NASA, the Smithsonian Scholarly Studies Fund and Eolas, the Irish scientific funding agency.

APPENDIX A

CALCULATION OF IMAGE PARAMETERS

Suppose the ith phototube is given coordinates x_i, y_i (in degrees) and registers a signal s_i. The origin of the coordinates will be the center of the array of phototubes. We define

$$\langle x \rangle = \frac{\Sigma s_i x_i}{\Sigma s_i}, \qquad \langle y \rangle = \frac{\Sigma s_i y_i}{\Sigma s_i},$$

$$\langle x^2 \rangle = \frac{\Sigma s_i x_i^2}{\Sigma s_i}, \qquad \langle y^2 \rangle = \frac{\Sigma s_i y_i^2}{\Sigma s_i}, \qquad \langle xy \rangle = \frac{\Sigma s_i x_i y_i}{\Sigma s_i},$$

$$\sigma_{x^2} = \langle x^2 \rangle - \langle x \rangle^2, \qquad \sigma_{y^2} = \langle y^2 \rangle - \langle y \rangle^2, \qquad \sigma_{xy} = \langle xy \rangle - \langle x \rangle \langle y \rangle .$$

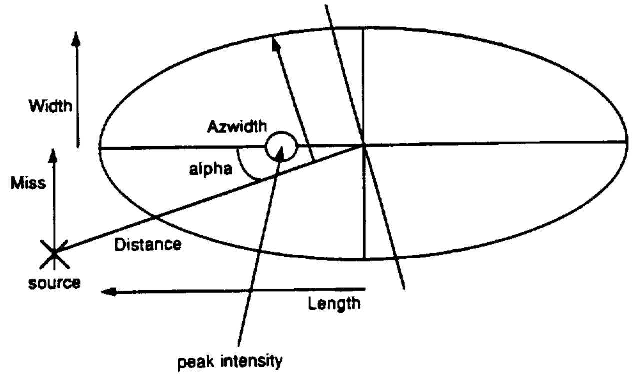

FIG. 11.—Definition of the image parameters

If $d = \sigma_{y^2} - \sigma_{x^2}$ and $z = [d^2 + 4(\sigma_{xy})^2]^{1/2}$ then

$$\langle \text{Length} \rangle^2 = \frac{\sigma_{x^2} + \sigma_{y^2} + z}{2}, \qquad \langle \text{Width} \rangle^2 = \frac{\sigma_{x^2} + \sigma_{y^2} - z}{2},$$

$$\langle \text{Distance} \rangle^2 = \langle x \rangle^2 + \langle y \rangle^2, \text{ and } \langle \text{Azwidth} \rangle^2 = \frac{\langle x \rangle^2 \langle y^2 \rangle - 2\langle x \rangle \langle y \rangle \langle xy \rangle + \langle x^2 \rangle \langle y \rangle^2}{\langle \text{Distance} \rangle^2}.$$

If $u = [1 + (d/z)]$ and $v = 2 - u$, then

$$\langle \text{Miss} \rangle^2 = \frac{1}{2}(u\langle x \rangle^2 + v\langle y \rangle^2) - \left(\frac{2\sigma_{xy}\langle x \rangle \langle y \rangle}{z}\right).$$

The angle Alpha is defined as

$$\text{Alpha} = \sin^{-1}\left(\frac{\text{Miss}}{\text{Distance}}\right).$$

The image parameters are indicated in Figure 11.

APPENDIX B

THE "SUPERCUTS" IMAGE ANALYSIS PROCEDURE

Given the presence of a strong signal in the Crab Nebula data, it was possible to empirically develop analysis procedures which optimized the high-resolution camera sensitivity. These procedures involved pedestal determination and noise suppression, and used multivariate cuts to optimally separate the gamma-ray signal from the cosmic-ray background. Details of the various analysis stages are presented below.

Pedestals.—The analog-to-digital (ADC) pedestals and their root mean square (rms) deviations are calculated directly from the data, which involves two passes through the data for each run.

On the first pass, the pulse-height spectrum for each tube for the entire run of several thousand events is determined. As a first approximation, a Gaussian curve is fitted to this spectrum up to the maximum point; the pedestal and its rms deviation is taken as the center and standard deviation of this curve.

On the second pass, the pulse-height spectra are calculated again, but this time any tube is omitted which contains, or is adjacent to, a tube which contains a signal; a tube with a signal is defined as one which has over 4 times its rms deviation after pedestal subtraction. Individual pedestal values are taken as the median values of such spectra for every tube, and the rms deviation is taken as the standard deviation of a fitted Gaussian centered on the pedestal.

For observations taken in 1991, the system was triggered artificially at regular intervals during each run to accumulate pedestal events relevant to each source or background region. These events were then used to evaluate the pedestals and rms deviations, and the procedure outlined above was not required.

Noise.—Instead of a simple global threshold (Vacanti et al. 1991), two thresholds are defined. The picture threshold is the multiple of the rms pedestal deviation which a tube must exceed to be part of the picture, and the boundary threshold the multiple which tubes adjacent to the picture must exceed to be part of the boundary (Fig. 12). The picture and boundary together make up the image; all other tubes are set to zero. Initially, the Crab 1988–1989 standard data base was parameterized at different values of picture and boundary threshold in order to determine their optimum values. Figures 13*a* and 13*b* show the variation in the signal (number of sigma) over the picture/boundary threshold plane, which was sampled at the points shown. For the standard Azwidth cut (Vacanti et al. 1991), the use of a boundary does not give a significant improvement over the 10 digital count noise threshold cutoff, or indeed over a cutoff based on rms deviations in the tubes (Fig. 13*a*). However, when sets of parameters are used, the

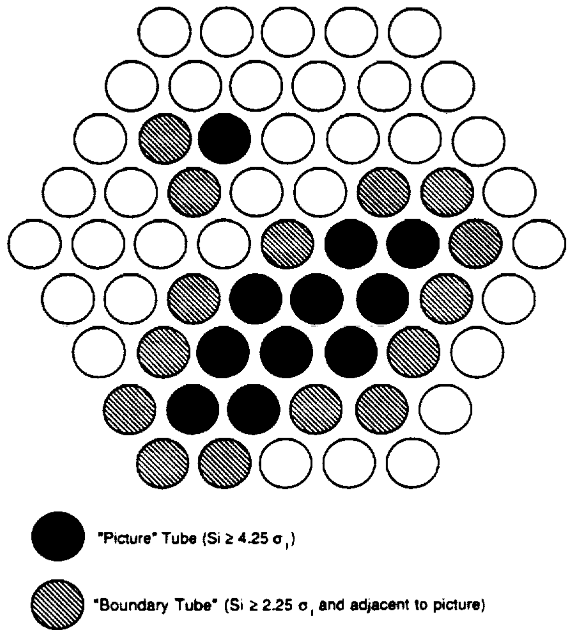

FIG. 12.—Illustration of the picture and boundary thresholds used to isolate the Cerenkov image (based on a subset of the photomultiplier array)

improvement is appreciable. One such set which was tested on the data consisted of the parameters Distance, Azwidth, Length, and the ratio of Width to Azwidth (Aharonian et al. 1991; Chilingarian & Cawley 1991). As is evident in Figure 13*b*, there is a peak in excess of 30 σ at a picture threshold of 4.25 and a boundary threshold of 2.25. If, however, both picture and boundary thresholds are made equal (equivalent to using a picture threshold alone), the significance drops to 27 σ.

Gains.—With the previous camera it had been found necessary to use relative gains derived from the data, since individual photomultipliers had very different spectral responses; the tubes used in this new camera had a common history, and it was found that the comparative gains determined from nitrogen spark triggered test exposures were satisfactory.

Cut values.—In determining the parameter cuts, the same data base was used. It was decided to substitute a Width cut for the Azwidth cut in the set since this would allow separation of the shape and orientation elements of the cut. For the orientation cut, a

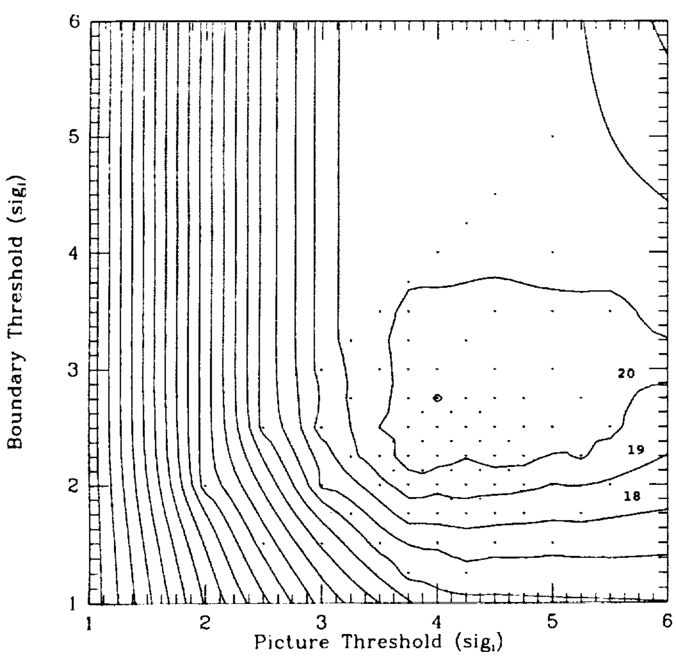

FIG. 13*a*

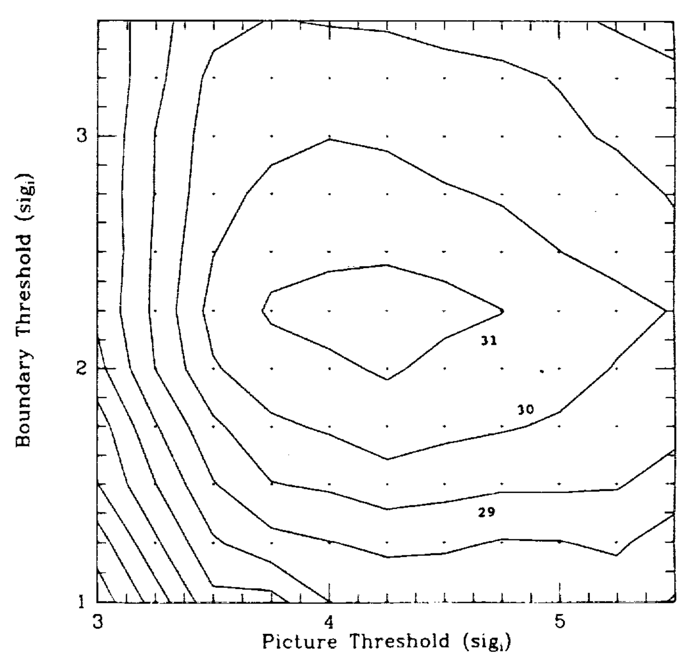

FIG. 13*b*

FIG. 13.—Contour plot of the variation in significance from the Crab Nebula standard data base with picture and boundary thresholds, (*a*) using the Azwidth cut and (*b*) using a multiparameter cut. The points indicate sample points.

parameter "Alpha" was defined as the angle between the major axis of the image and the line joining the image centroid to the center of the field of view (Appendix A).

The dependence of the Width and Length upper cut values on size was investigated by checking the optimum cut values when showers under various sizes were excluded. No significant change in the optimum cut value was found.

It was found empirically (and confirmed by simulations) that the introduction of a lower bound on the Distance cut could improve the signal. This amounts to excluding events close to the optic axis, whose orientation is not well-defined.

The optimum cut values determined are as follows:

Shape discrimination:

$$0^\circ\!.073 < \text{Width} < 0^\circ\!.15$$

$$0^\circ\!.16 < \text{Length} < 0^\circ\!.30$$

Orientation discrimination:

$$0^\circ\!.51 < \text{Distance} < 1^\circ\!.1$$

$$\text{Miss/Distance} < 0^\circ\!.26 \text{ (equivalent to Alpha} < 15^\circ) .$$

The use of a zenith-angle dependence for the upper bound of the Width and Length cuts was investigated but was found to give no improvement in signal, so this was not used in the standard. Note that the range of zenith angle in this data base was restricted to <35°. It was found that the same selection works effectively on Crab data out to zenith angles of 45°.

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OUTBURST OF TEV PHOTONS FROM MARKARIAN 421

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ABSTRACT

Markarian 421, an active galactic nucleus of the BL Lacertae type is the closest EGRET detected AGN. It has been monitored by the Whipple Observatory very-high-energy γ-ray telescope since its discovery at TeV energies (Punch et al. 1992), for approximately 90 nights, totalling 130 hours of observation. Observations 23 Dec 1993 - 10 May 1994 showed an average source flux only 1/2 that of its 1992 discovery level. However, observations on 14 and 15 May 1994 show an increase in flux above this quiescent level by a factor of $\sim$ 10. The timescale of this increase provides the best geometric constraint on the extent of TeV photon emission regions within AGN's. The observation of the high TeV flux occurred 1 day prior to the observation by the ASCA satellite of a very high 2-10 keV X-ray flux (Takahashi et al. 1994). This strong TeV outburst is reminiscent of the behavior seen for the stronger 100 MeV-GeV EGRET sources (e.g. 3C279, Kniffen et al. 1993), but was not anticipated in view of the fact that the six EGRET observations of Mrk 421 from 1991 June to 1993 July (Lin et al. 1994) showed no evidence for variability.

Subject headings: BL Lacertae objects: general–BL Lacertae objects: individual (Markarian 421)–gamma rays: observations

To be published in The Astrophysical Journal Letters January 10, 1995

1. INTRODUCTION

The full-sky survey by the EGRET gamma-ray detector (Fichtel et al. 1994) has reported detections of nearly 40 active galactic nuclei (AGN's) at photon energies above 100 MeV. At other wavelengths, these sources are all bright, flat spectrum radio sources with, in many cases, optical polarization and rapid optical variability, characteristics of the blazar class of AGN. (Dermer and Schlickeiser (1992), and Antonucci (1993) are useful guides to AGN taxonomy. In the simplest, unified picture of the AGN phenomenon, blazars are those AGN's which have associated jets with the jet axis orientated near the observer's line-of-sight.)

The gamma-ray luminosities inferred from the EGRET observations are in the range of 10^{44} to more than 10^{49} ergs/s if one assumes isotropy. However, the true luminosities will be several orders of magnitude less if the gamma-rays are associated in some way with the relativistic jets of the blazars and are thereby beamed. Most models that have been advanced to account for the gamma-rays make this assumption.

The closest EGRET source is Markarian 421 at a red-shift z=0.031. Mrk 421 is a BL Lac object extensively observed at radio (Owen et al. 1978, Zhang and Bååth, 1990), uv/optical (Maza, Martin, and Angel 1978; Mufson et al. 1990), and X-ray frequencies (Mufson et al. 1990, Mushotsky et al. 1979, George, Warwick & Bromage 1988). Its parent galaxy has been identified as a giant elliptical (Ulrich et al. 1975; Mufson, Hutter, and Kondo 1989). Variability has been observed in X-rays and at lower photon energies, with a time scale of days (optical, Xie at al. 1988) to hours (X-ray, Giommi et al. 1990). However, Mrk 421 has not been observed to vary at EGRET energies in spite of the fact that it has been observed a total of 6 times during phase 1 (16 May 1991 - 17 October 1992) and phase 2 (17 October 1992 - 7 September 1993) of the Compton Observatory program (Lin et al. 1994). All six observations were consistent with a constant, relatively weak flux above 100 MeV of

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$(1.7 \pm 0.3) \times 10^{-7}$ photons/cm^2/s. In Michelson et al. (1994) Mrk 421 was considered a notable exception to the variability which has been generally associated with the other EGRET AGN sources.

In 1992 Mrk 421 became the first (and as yet, the only) EGRET source to be detected at higher energies. The Whipple Observatory collaboration reported its detection at a significance of 6.3σ (Punch et al. 1992) for photon energies above 500 GeV. Since its discovery as a TeV source, Mrk 421 has been monitored by the Whipple Observatory very-high-energy γ-ray telescope (Cawley et al. 1990) for approximately 90 nights, totalling 130 hours of on-source observation with a comparable amount of time off-source. Observations 23 Dec 1993 - 10 May 1994 showed an average source flux only approximately 1/2 that of its 1992 discovery level (Schubnell et al. 1994). However subsequent observation showed a strong increase to a level (on May 15.25 UT, 1994) approximately 10 times the "quiescent" 1993-94 flux, rising to this level within a period of 5 days. At this high level, Mrk 421 was brighter at TeV energies than the Crab Nebula (Vacanti et al. 1991). The outburst detected by the Whipple Observatory is strongly reminscent of the behavior seen at EGRET energies for the bright EGRET source, 3C279 (Kniffen et al. 1993), in which this source varied by a factor of five over several days. A possible correlated flare, in the 2-10 keV X-ray band, has been reported by Takahashi et al. (1994) for Mrk 421 from ASCA observations. The ASCA observations began approximately 1 day after the observation of the TeV high state.

In the following section observational details of the TeV outburst and its analysis are given. In a concluding section, a discussion of the implications of these observations and possible constraints that they place on theoretical models of AGN's are presented.

2. OBSERVATIONS, ANALYSIS, AND RESULTS

The very-high-energy γ-ray telescope (Cawley et al. 1990) at the Whipple Observatory employs a 10 m diameter reflector to image Cherenkov light from air showers onto a two-dimensional array of 109 fast photomultipliers (pmts) with a pixel size of 0.25°. Since 1992, the 10 m telescope has been improved in a number of respects, with completely recoated mirror facets and somewhat lower electronic thresholds for its camera elements. The camera itself has been upgraded. Its outer ring of 18 5.08 cm diameter pmts has been replaced with 18 2.86 cm diameter pmts. Most recently each pmt was surrounded by a simple light funnel which captured Cherenkov light previously lost to the space between the pmts. The net result of these improvements is a reduction in effective threshold of the telescope to 250 GeV, with a cosmic-ray shower counting rate of 9 showers/s.

Monte Carlo simulations (Hillas 1985, Macomb and Lamb 1990), repeated observations of the Crab Nebula by the Whipple collaboration (Vacanti et al. 1991), and observations by the CANGAROO group using the imaging technique (Tanimori et al. 1994) demonstrate that the Cherenkov light images of air showers induced by γ-rays can be reliably distinguished from those induced by cosmic rays (*i. e.*, nucleons). The most sensitive technique yet used by the Whipple group for this purpose, "supercuts" (Punch et al. 1991, Reynolds et al. 1993), uses four parameters to characterize the roughly elliptical shape of γ-ray shower images. Two of the parameters specify the shape of the image, and a third gives its location relative to the center of the field of view. The fourth parameter, "alpha", is the angle between the major axis of the shower image and a line from its centroid to the assumed source location in the image plane. For γ-ray showers from a point-like source, alpha should be small.

In figure 1, the on- and off-source alpha distributions for the 15.25 May 1994 observations of Mrk 421 are shown. The distributions are for those events which have satisfied the selection criteria for the other three parameters. In figure 1 a) no further selection is made. In figure 1 b) only those showers with a total digital signal greater than 500 digital counts are selected. (This selection corresponds to an increased threshold of $\sim$ 500 GeV, consistent with the threshold of the original Whipple 1992 detection; Punch et al. 1992.)

A very strong excess near zero degrees is apparent in both datasets. In a), in the region of alpha <15° (the standard supercuts alpha-cut value), there is a 6.5σ excess, with 254 on-source showers and 127 off-source showers. (The substitution of smaller pixel pmts in the camera's outer ring gave better angular resolution but reduced the 1992 field-of-view from 3.9° to 3.0°. This field-of-view reduction causes the alpha distribution for off-source showers to decrease somewhat for angles beyond 75°.) The duration of both the on- and off-source observations is 28.3 minutes. The difference in the two distributions gives a γ-ray counting rate 4.5±0.7 photons/minute. The effective collection area for gamma-rays above 250 GeV is 3.5×10^8 cm^2. Thus this excess corresponds to a flux of $2.1 \pm 0.3 \times 10^{-10}$ photons cm^{-2} s^{-1} above 250 GeV. This flux level is 9 ±1.5 times the average flux observed Dec 1993-April 1994 (Schubnell et al. 1995), which we take to be representative of a "quiescent" level. Possible systematic errors in the effective collection area give the flux quoted an additional overall ±30% uncertainty; in addition there is a possible sytematic uncertainty in the energy threshold of ±30%.

The photon rates for Mrk 421 derived from observations 10 - 15 May and 29 May - 12 June are shown in figure 2. The errors on the points are purely statistical. Possible systematic errors due to changing sky conditions and zenith angle variations are small, and, to some extent measurable, with the raw shower counting rate in the telescope being the principal diagnostic. Using this diagnostic we estimate that there is an additional uncertainty of ±10% in the rates shown in figure 2. The observations were taken in two modes: an on/off mode in which equal time is given to on- and off-source observations, and a tracking mode in which only on-source data is taken. In order to establish an off-source background for the tracking runs a background template taken from the sum of all off-source runs was used.

The observations prior to 15 May (day 135) clearly show a rising rate consistent with an e-folding time of ~2 days. This is the first, clearcut case for variability in the TeV region for an extragalactic object on such a short timescale. In addition, a second region of enhanced emission of lesser significance, peaking on 7 June (day 158) 3σ above the quiescent level and confined to an interval of 4 days, is evident as well.

While there are still large systematic uncertainties in the absolute energy spectra derived from imaging Cherenkov detectors, it is possible to compare the energy spectrum in the high and low intensity states. A preliminary analysis shows no change in the previously measured spectral index (Mohanty et al. 1993) by more than ± 0.5 at the 90% confidence level.

3. DISCUSSION

No variability in the gamma-ray emission from Mrk 421 has been reported previously by EGRET at MeV-GeV energies (Lin et al. 1994). This is uncharacteristic of such emission from blazars and has led to the suggestion by the EGRET group (Michelson et al. 1994) that Mrk 421 is qualitatively different from the bulk of the EGRET detected AGN's. However, the strong TeV outburst with a time-scale of a few days reported here is reminiscent of the behavior seen for the stronger EGRET sources (e.g. 3C279, Kniffen et al. 1993). This suggests that, at least at TeV energies, Mrk 421 exhibits approximately the same degree of variability that the other EGRET AGN sources do.

The time of the peak flux of figure 2, 15.25 May 1994, precedes by 27 hours the beginning of an ASCA X-ray satellite observation from 16.4 - 17.3 May. The X-ray flux observed (Takahashi et al. 1994) was approximately 20 times the normal quiescent level of the 2-10 keV flux (George, Warwick &Bromage 1988). The near simultaneity of the two high states confirms the appropriateness of the TeV source's identification with Mrk 421. The previous identification (Punch et al. 1992) was based on the location of the TeV source within 0.1° of the known location of Mrk 421; the ASCA X-ray detector pin-points the source to less than an arc minute.

Variability for active galactic nuclei (AGN's) may be a useful diagnostic in constraining the physical environment of the massive black-holes which are thought to be their ultimate power source. For the BL-Lac sub-class of AGN, the usual light travel time argument must be used with care, inasmuch as these objects are thought to have their relativistic jets oriented near to the line-of-sight to the earth (Antonucci 1993), and, as discussed in the introduction, the gamma-rays are generally thought to be associated with the jets.

The limits to the spatial extent over which the TeV radiation occurs depends very much on the model for production. We consider two limiting cases representing two mutually exclusive extremes. In one extreme case we take the radiation to be emitted from a highly localized wavefront moving directly towards the observer with velocity, βc. Under this assumption, the duration of emission in the wavefront comoving frame is (Zdziarski, Svensson &Paczyński 1991) is:

$$\Delta t_{com} = \frac{1}{\gamma(1-\beta)}\Delta t_{obs} \simeq 2\gamma\Delta t_{obs}$$

where Δt_{obs} is the characteristic duration of the observed emission outburst, 2 days. In the observer rest frame, the wavefront travels a distance, $2\gamma^2 c\Delta t_{obs}$. For a jet bulk velocity with γ of order 10, a value suggested from very long baseline radio interferometric observations of superluminal jets (e.g. Pandovani and Urry 1992), the maximum distance the wavefront travels along the jet axis would be stretched to ~1 light year. This is an extreme upper limit, which may be physically unreasonable if the radiation is due to the inverse Compton process from a population of relativistic electrons. If the magnetic field close to the AGN center is appreciably higher than in the outer lobes, electrons of appropriate energy could not survive for such a long time, and then the 2-day observed duration would represent the actual duration (in our frame) of the injection of high energy particles.

The other limiting case that we consider is that of a causally-linked volume emitting radiation at its boundary. If the volume is at rest with respect to the observer, its characteristic size, Δr, is simply $c\Delta t_{obs} \simeq 2$ light days. If the volume is a sphere moving with velocity, βc, towards the observer, the combined effects of Lorentz contraction and Doppler shift yield:

$$\Delta r_{com} = \frac{1}{\gamma(1-\beta)}c\Delta t_{obs} \simeq 2\gamma c\Delta t_{obs} \simeq 0.03 \text{ parsecs} \qquad (\gamma=10)$$

This last expression may be of interest for models of γ-ray production which generate photons from shock acceleration of particles in the body of the AGN jet.

The degree to which the X-ray and TeV high states coincide is uncertain because of the limited duration of the X-ray observation, May 16.4-17.3 UT, and the limited sampling of the TeV observations. A maximum duration of the first TeV high intensity state is $\sim$10 days. The duration of the X-ray high state is unknown. Previous monitoring of Mrk 421 at X-ray energies (George, Warwick & Bromage 1988; Makino et al. 1987; Giommi et al. 1990) has shown that such X-ray high states are relatively rare, consistent with the observation that BL Lacs spend less that 10% of the time in flares that involve luminosity variation of factors of two or more (Giommi et al. 1990). Thus, if typical, the May X-ray flare may be relatively short-lived with a duration comparable to or less than our limit on the duration of the TeV high state. If this is true then the X-ray and TeV high states may be taken to be coincident to within $\sim$ 10 days. Future simultaneous X-ray and TeV observations will determine the extent to which these phenomena are correlated.

We thank Kevin Harris and Teresa Lappin for their considerable help in obtaining the observations. Useful discussions with Chuck Dermer are also acknowledged, as well as support from the US Department of Energy; NSF; NASA; the Smithsonian Scholarly Studies Research Fund; Forbairt, the scientific funding agency of Ireland; and the Particle Physics and Astronomy Research Council of Great Britain.

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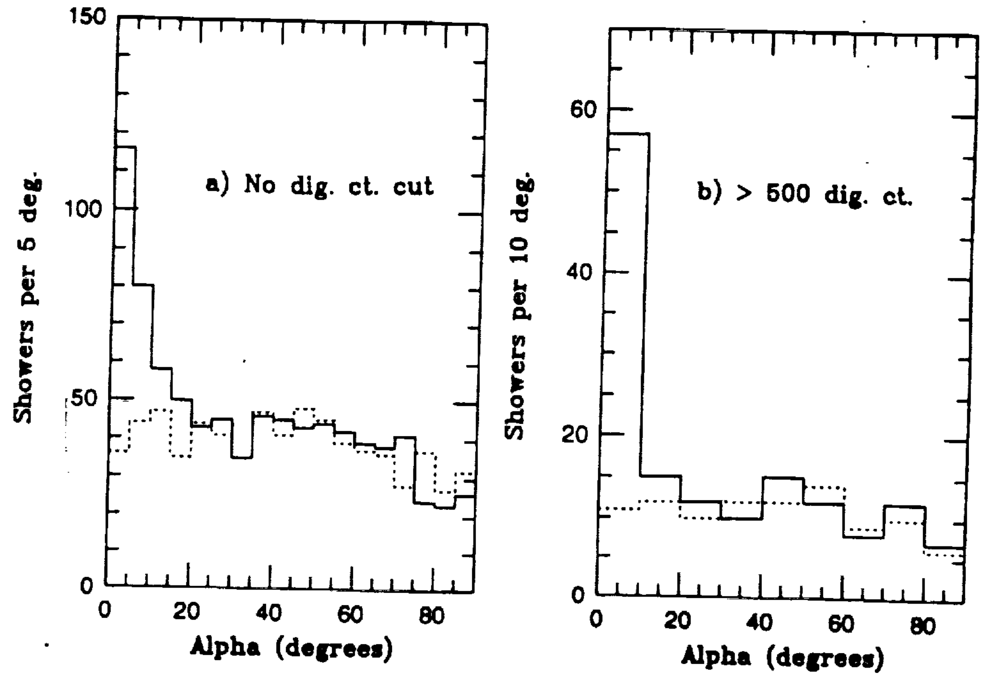

FIG 1. On- and off-source alpha distributions for Markarian 421 for 15.25 May 1994 (UT). The distributions are for those showers for which the other supercuts selection criteria have been satisfied. The duration of each observation is 28.3 minutes. a) No selection has been made on the number of digital counts contained in a shower image. b) Only those showers which have more than 500 digital counts are retained. This latter selection is approximately equivalent to raising the threshold energy from 250 to 500 GeV.

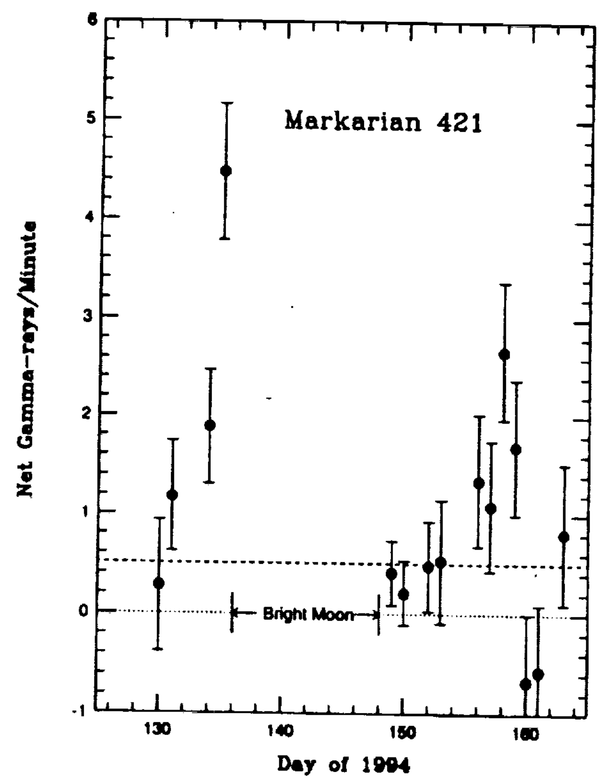

FIG 2. The variation in net gamma-rays/minute for the Markarian 421 observations from 10 May, 1994 (day 130) through 12 June, 1994 (day 163). The peak intensity of 15.25 May (day 135) occurs 27 hours prior to a reported X-ray high state (Takahashi et al 1994). Data from 16-28 May (days 136-148) were not obtained due to bright moon conditions. The dashed line shows the 1994 quiescent level (Schubnell et al. 1995).